

TERTIARY BASALTS OF THE BAFFIN BAY AREA



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Frontispiece. Columnar jointing in a flow of feldspar-phyric basalt overlying
a section of thin olivine basalt flows, Suvdlua, Svartenhuk.



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ABSTRACT

A stratigraphical and petrological "parallelism" exists between the Cape Dyer-Padloping Island area of Baffin Island and Svartenhuk Peninsula in west Greenland. The similarities between the basement rocks and between the pre-volcanic sediments of the two areas are briefly discussed. Relationships between the basalts are considered in greater detail.

The igneous rocks include subaqueous breccias of olivine-rich basalt, subaerial olivine-rich and olivine-poor basalt, feldspar-phyric basalt and trachyte, the last two not being found in the Baffin Island province. Chemically the basalts are regarded as members of a tholeiitic suite since all but two specimens contain normative hypersthene. At comparable levels of MgO, the basalts have similar major element chemistry, but minor and trace elements tend to be enriched in the Svartenhuk basalts by a factor of approximately 1.5. Even so, the two suites of minor and trace elements are sufficiently distinctive from those of other provinces to suggest a relationship between the two. The case for a genetic relationship is strengthened by evidence from variation diagrams, many of which illustrate a possible evolution of one group into the other. Evidence is presented to suggest that fractionation of olivine has been the principal method by which these compositions have evolved.

The basalt compositions have been projected into the simple normative basalt tetrahedron and modified CMAS tetrahedron, illustrating that the observed phase relations of these rocks do not conform with the phase relations as determined principally for Hawaiian rocks. Rather, their behaviour suggests conformity with phase boundaries intermediate between those for Hawaiian rocks and those of the synthetic system. Three petrogenetic models are considered. That involving partial melting of mantle peridotite with

the option of some degree of fractionation at 30 kb. seems best to account for both the picritic bulk composition and the low but disparate levels of minor and trace elements between the two basalt areas. Evidence that some degree of eclogite fractionation has been operative on the Svartenhuk parental magma includes the enrichment in incompatible elements, higher CaO/MgO and lower $\text{Na}_2\text{O/K}_2\text{O}$ ratios and a corroborative statistical evaluation of its occurrence.

A model is proposed for the opening of Baffin Bay by continental drift and is based on seismic, aeromagnetic, palaeomagnetic, palaeontological, geomorphological and structural relations in the Arctic. The principal features involve the progression of a rift valley northwards through what is now the Labrador Sea and Baffin Bay to a terminal point situated near the southeast corner of Ellesmere Island. This point became the fulcrum about which Greenland rotated counter-clockwise with contemporaneous volcanism in the rift, flexuring of the Variscan-age Franklinian fold belt and folding of sediments in the Sverdrup basin. The rotation and folding were discontinued when the Nares transform fault was created, from which time the motion of Greenland became one of translation along that fault.

Stratigraphic, structural and petrological evidence combine to suggest that the two Tertiary volcanic areas of Baffin Bay are the remnants of a formerly continuous igneous province.

I. Introduction

The locations of Maps 1 and 2, which cover the two areas of Tertiary volcanics described in this thesis, are shown in Fig. 1. This figure also serves to locate the positions of places referred to elsewhere in the thesis.

On the west side of Baffin Bay, the field operations of 1964 and 1965 were based in the settlement of Broughton Island. There provisions were obtained from the Hudson's Bay post, and arrangements were made for the hire of an Eskimo whaleboat and crew led by Pauloosie Kudluk. Pack-ice conditions on the sea during both summers prevented much of the proposed work from being done, and on neither expedition were we able to reach Padloping Island from the north before the first of August. From that date the field season is normally only 3-6 weeks long. However, in spite of these difficulties the main purpose of the investigation, to map and sample the lavas, was carried out with a reasonable degree of completeness, but little time remained for investigation of the Precambrian basement.

The Greenland field season in 1966 was based on board the Greenland Geological Survey (G.G.U.) ship "N.V. Ussing". Because of the counter-clockwise movement of currents in Baffin Bay, the area around Svartenhuk Peninsula is normally clear of pack-ice in June and, as a result, the following two months were completely unhindered in this respect. A small lifeboat was used for landing and especially for close inspection of the south coast of the peninsula. Two extended traverses were made up Simiutap kua and Qordlortup kua, but in the main it was felt that the well-indented coastline provided all the sections that were necessary. Furthermore, the long stretch of the south coast is nearly perpendicular to the regional strike, thereby allowing a

Fig. 1. Place Names in the Arctic and Location of the Two Geological Maps.

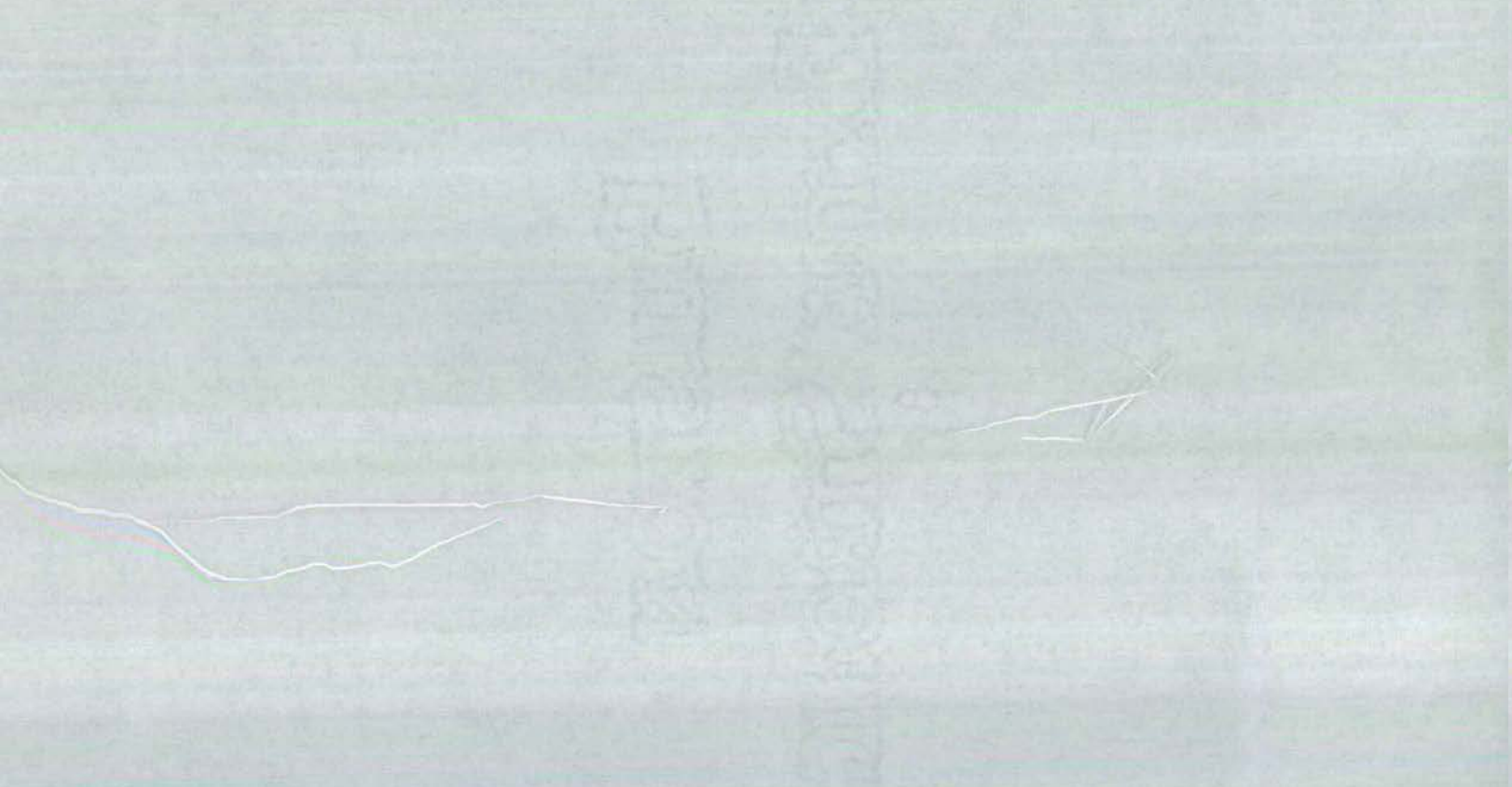




FIG. 1

complete section to be observed. Mapping of the interior of the peninsula was accomplished from various coastal hilltops with the aid of binoculars and aerial photographs. The three main units in the volcanics, (i) cross-bedded breccia, (ii) gray-weathering, soft, olivine-rich basalts and (iii) brown-weathering, resistant, feldspar-phyric basalts, were distinguishable with suitable lighting at distances up to 15 km. The geological map of Svartenhuk (Map 2 in the pocket) is an advance over previous presentations in that it makes the distinction between the two main subaerial lava types and portrays some structural elements not previously recognized.

II. Previous Work

A) Baffin Island

The first recorded account of there being something other than crystalline basement rocks along the Baffin Island coast is by Sutherland (1853), who wrote, "I believe there is one exception at Cape Durban, on the 67th parallel, where coal has been found by the whalers; and also at Kingaite, two degrees to the southwest of Durban, where, from the appearance of the land as viewed from a distance, trap may be said to occur on both sides of that inlet." Recent work by Riley (1960) in Cumberland Sound, into which Kingnait (or Kingaite) Fiord runs, makes no mention of any lavas in this region. If any further outcrops of the lavas are found inland, then the most likely place is the low ground between Padloping Island and Pangnirtung and Kingnait Fiords. McMillan in a report by Bernier (1910) makes reference to the "volcanic agglomerates" of Cape Searle and even established that the sediments on Durban Island were of Tertiary age. Again a long period of time elapsed before Kidd (1953) published an account of his reconnaissance observations; but no petrological work was ever published. Since the beginning of the

current research programme in 1964, preliminary results have been presented in the form of two brief publications (Wilson and Clarke, 1965; Clarke, 1967) and an introductory account of the stratigraphy and petrography in an unpublished thesis presented for an M.A. degree at University of Toronto (1965). The present thesis is the first attempt to discuss fully the chemical features, petrogenesis and associated tectonics of the lava field.

B) Svartenhuk Peninsula, West Greenland

Since a very comprehensive account of the history of geological exploration in Svartenhuk has been given in Rosenkrantz et al. (1942), a recapitulation is unnecessary. However, tribute should be paid to the intrepid K.J.V. Steenstrup who, in 1878 and 1879, made exhaustive traverses around the peninsula in an open boat. In 1883 he published the first detailed map of the peninsula, most of which remains unaltered today. Other maps appeared during the next fifty years but even the contribution of L. Koch (1929) did not improve on Steenstrup's work. It was not until 1942 that a map showing the interior of the peninsula as well as the coastal geology was published (Rosenkrantz et al., 1942), and at the same time Noe-Nygaard (1942) published an account of some petrological aspects of the Svartenhuk lavas.

The present work on Svartenhuk has been conducted in collaboration with T.C.R. Pulvertaft of the Greenland Geological Survey (G.G.U.). A map is in preparation for publication and an explanatory account has already been presented (Pulvertaft and Clarke, 1966). Furthermore, a brief account relating lava chemistry to stratigraphy has also been published (Clarke, 1968). The large-scale map of Svartenhuk (Map 2) is the product of both field collaboration between the author and Pulvertaft, and subsequent air-photo interpretation by Pulvertaft.

III. Research Objectives

In an earlier petrological thesis (1965) the author concluded that, if a solution were sought to the question of the feasibility of continental drift in Baffin Bay, the answer would be more readily obtainable through a palaeobotanical investigation. Consequently, the drift aspect was dropped and the current phase of the work began entirely as a study of the geochemistry and petrogenesis of the Baffin Island basalts. However, very early in the analytical work it became apparent that these rocks exhibited some highly unusual characteristics. It then seemed possible that a detailed chemical investigation of basalts from both sides of Baffin Bay could make a contribution towards the solution of the continental drift problem. If a satisfactory degree of correlation could be shown to exist between the two groups of lavas, then severing of a formerly continuous lava province into two parts symmetrically disposed across a rift would become an attractive proposition.

In general, the work can be broken down into four categories, all of which contribute, directly or indirectly, to the central theme of correlation and continental drift:

- 1) field relations in both volcanic provinces and a stratigraphic comparison between the provinces
- 2) a geochemical study of the lavas and statistical evaluation of the probability of the lavas having been derived from one magma batch
- 3) the petrogenesis of the basalts involving an application of phase equilibrium studies
- 4) implications for continental drift based on the present work and on published material by other authors, combined with a reconstruction of the Baffin Bay region in pre-Tertiary times

I. Baffin IslandA) General

Revived interest in the whole idea of continental drift, especially as applied to the North Atlantic, has led to the study of the hitherto almost completely ignored basalts of southeastern Baffin Island. Complete coverage of the area selected for field work was obtained on 1:63,000 aerial photographs. Examination of these photographs revealed about 20 major, separate outcrops of lava lying along a narrow coastal strip northwestwards from Cape Dyer (approx. Lat. 67° N., Long. 61° W.) for a distance of some 90 km. to Cape Searle. All of the outcrops are restricted to within 8 km. of a straight line drawn between the two capes, approximating the general coastline (Map 1, in pocket). None is larger than 10-15 km.² in area and the average size is considerably smaller.

The three major geological units exposed along the coast are the Precambrian basement, relatively minor early Tertiary terrestrial sediments and a succession of younger picritic basalts usually preceded by a relatively thin formation of volcanic breccia. In general, the volcanics have been extruded onto an irregular erosion surface on the Precambrian basement, but in some cases they lie on the terrestrial sediments upon which they are conformable, or nearly so.

Evidence suggests that the breccias are subaqueous in origin. On the assumption that the tops of these breccias were all close to sea-level at the time of formation, there must have been slight differential movements of the main outcrops during a post-volcanic, epeirogenic adjustment, involving an uplift of up to 400-500 m. The single exception to this extent of movement

is Cape Searle Island, where the top of the breccia on the sea-stacks is only about 150 m. above sea-level, but the major units have remained horizontal. This suggests that the present stratigraphic elevation of Cape Searle is not attributable to the episode of recent coastal slumping, which takes place along curving fault planes (concave seaward), producing tilted blocks. On Durban Island the possible presence of a small graben structure filled with pre-volcanic sediments is evidence that extensional faulting was an early feature of the province. In this respect, then, it bears similarities to the west Greenland province, which is discussed later.

B) Precambrian Basement

Although the basement was not the main object of investigation, observations of a general nature were made on the composition and attitude of the gneisses. However, the structures have proven to be on too small a scale to allow even broad generalizations about the tectonic history of the area.

Compositionally, the gneisses and migmatites outcropping along the 145 km. of coast from Broughton Island to Cape Dyer are reasonably uniform. The usual mineralogy is quartz - 2 feldspars - biotite frequently with garnet and/or muscovite plus apatite, zircon and magnetite as the most frequent accessories. The grade of metamorphism is mostly amphibolite facies, locally being raised to granulite facies.

In some areas such as Merchant's Bay, ultramafic layers of biotite amphibolite and pyroxenite, often showing boudinage, are especially prominent, and sometimes extend for distances of several kilometres along strike. Determinations for Ni on three of these bands yielded values of 600, 850 and 1500 ppm. This suggests that they may be the remnants of ultrabasic material rather than metamorphosed mafic horizons in the original sediments.

The gneisses and migmatites are liberally cut by quartzo-feldspathic pegmatites often bearing garnet, biotite, muscovite and, more rarely, tourmaline. On Durban Island a non-foliated muscovite-tourmaline granite occurs and is almost certainly the source of the distinctive pre-volcanic tourmaline-bearing sediments on the island. Several large gossans appear along the coast and are associated with a pyrite-pyrrhotite mineralization. However, nothing of economic value was found.

C) Pre-volcanic Sediments

At most of the localities the volcanics are underlain by sediments. These consist mainly of unconsolidated white quartz sands, impure sandstones, shales, minor coal and conglomerate horizons, all apparently of terrestrial origin (Plate I). This conclusion as to the environment of deposition is indicated by the predominant current cross-bedding, lack of marine fossils, abundance of plant fossils and a good section of fluvial conglomerates. From a cursory examination of the fossil flora, Dr. W. A. Bell (pers. comm.) has ascribed these rocks to the Palaeocene, which is taken as the period 65-58.5 my. ago (Harland et al., 1964). A potassium-argon age determination of 58 ± 2 my. has been obtained on the lavas by Dr. E. Farrar (pers. comm.) which agrees well with Bell's assessment for the sediments. Although no detailed work has been done on the fossil collection, a preliminary survey has shown that the floral assemblage is not unlike that contained in the Upper Atanikerdruk series of west Greenland, described by Koch (1963). The two most common and readily identifiable species on Baffin Island are Metasequoia occidentalis and Credneria spectabilis (Heer), both of which are described by Koch as occurring in the Lower Palaeocene of Nugsuak.

A typical sedimentary section some 150 m. thick exists on the north side

of Cape Searle Island. This sequence consists of an alternation of unconsolidated white sands and thinner friable black shales. The bases of the sandy horizons are often marked by large botryoidal concretions of sand and carbonaceous matter. The nature of the cross-bedding in the sands generally points to a southwesterly source area for this formation. At Cape Searle and other localities, the sedimentary sequences exhibit a synformal or gentle basin-like structure due, at least in part, to minor faulting within the strata, but the age of the faulting could not be deduced.

The unconsolidated nature of the sediments facilitates undercutting of the lavas and the eventual formation of long talus slopes and landslips. The talus then tends to obscure the relationships between the sediments and the basement rocks, but the slumps often provide excellent exposures of the sediment-volcanic contacts. Where the sediments are overlain by volcanic breccias it is often possible to find thin tuffaceous bands in the sediments within one or two metres of the main contact. Where the sediments are overlain by subaerial lava flows it is possible to find thin intercalating bands of sediments between the first few flows, whereas in the breccia localities the commencement of volcanism completely ended any further sedimentation. This is partly because of the presumed rapid formation of the breccias, coupled with the fact that they appear to have progressed in the manner of an advancing delta front with a steeply dipping surface of their own fabrication. This will be discussed in the next section.

As mentioned earlier, sediments of a different nature are found on northeastern Durban Island. There the lower 35 m. consist of coals and friable black shales, and these are followed by up to 250 m. of somewhat reddened, well-consolidated, tourmaline-bearing arkoses. This unique accumulation of arkose is easily traced to erosion of the granite on the same island.

Deposition has probably been localized by repeated movement on a fault at the extreme northeast end of the island. In fact, a small graben may have formed (although the western contact of sediments against Precambrian is by no means certain), and this could account for the considerable thickness of uniform sediments derived from a fairly small granite boss.

The only generality that can be drawn with regard to the sediments, other than those of Durban Island, is that they increase in both thickness and frequency from Cape Dyer northwards to Cape Searle.

D) Tertiary Volcanics

Since the volcanic outcrops show largely identical features, the characteristics held in common are listed below:

- a) no outcrop occurs more than 8 km. inland from the nearly linear east coast
- b) a cross-section of any outcrop taken perpendicular to the coastline exhibits a prominent seaward-facing cliff and a rapid thinning of the lava succession inland
- c) there is no evidence of Pleistocene glaciation on top of the outcrops either in the form of striations or glacial erratics
- d) lavas appear to occupy former depressions in the Precambrian basement
- e) breccia is often the basal volcanic member and usually overlies thick accumulations of sediment
- f) although the thickness of individual lava flows ranges from 1-35 m., flows thicker than 10 m. are rare
- g) the attitude of flows in most outcrops is horizontal except when tilted as a result of slumping caused by undermining of the sediments immediately beneath the lavas

- h) the flows become noticeably thinner towards the top of each section
- i) flow tops become increasingly reddened towards the top of each section
- j) the composition of the flows varies little throughout the region, all being picritic or olivine-rich basalts

The most complete succession of volcanics occurs at Cape Searle, where at least 150 m. of breccias exist (their base being below sea-level) and approximately 300 m. of subaerial flows are exposed (Plate II). Detailed investigation of this succession is impossible because of the vertical cliffs which surround the cape. Other outcrops have considerably lesser thicknesses of breccia and usually a thinner succession of flows. A discussion of the three volcanic elements - the breccias, subaerial flows and dykes - now follows.

(1) Breccias

The breccias may be divided into two groups solely on the basis of their over-all colour in the field, namely, orange and black. Both types are characterized by a large proportion of hyaloclastite (Rittmann, 1962), basaltic fragments and massive basaltic blocks. In the black breccia the coarse basalt is normally enclosed in a rim of sideromelane and is often distinguishable as long, thin, non-brecciated dribblets or tongues in the cross-bedded sequence (see below). On the other hand, the crystalline blocks in the orange breccia are much more finely comminuted. Each fragment usually possesses one surface encrusted with basaltic glass and often these fragments have a conical shape, suggesting that they are the exploded remnants of larger blocks. Plate III illustrates the large-scale texture of the orange breccia. In addition, where breccia is found horizontally stratified with graded bedding it is

always of the orange variety. These features lead to the conclusion that, colour apart, the orange breccia is simply the more finely fragmented equivalent of the black breccia. The difference in colour is merely a consequence of the greater degree of hydration of the glass in the more finely comminuted material. In contrast, the larger fragments of black breccia expose less surface area for alteration and, as a result, the extent of alteration is only that of dark green rims of palagonite around the unaltered sideromelane. The type and degree of alteration in these breccias, their high water contents and stratification, combined with the prolific amounts of basaltic glass all suggest a subaqueous origin for these initial extrusives.

A model to explain the major structures in the Baffin Island breccias is presented in Fig. 2. The mechanics have already been discussed by Fuller (1931, p. 284) and Jones (1966). A paragraph from the former states, "A fluid lava on encountering a local body of water would tend to granulate like molten slag and would thus form a fine breccia which would accumulate to a depth approximately equal to that of the water. The fine breccia would settle until its surface attained an angle of repose which, owing to the roughness of the fragments, would be relatively steep. If the molten cascade continued to pour into the water, the accumulation of granulated glass would gradually advance like the foreset bedding of a delta. The inclined bedding would be preserved by the thin sheets and the ropy ellipsoidal masses, which failed to granulate. Except for the possible effect of rising steam, the flow would gradually advance on top of these foreset beds as if on dry land." This description covers all but the patchy development of the horizontally stratified material mentioned above. These localized prisms of sorted material normally occur at the top of the breccia sequences and are probably due to sorting of fragments in shallow water. Where such horizontal stratification is seen lower in a

Fig. 2. Model for the Formation of Basalt Breccia and Production of a Typical Cross-Section on Baffin Island Looking North. (Greatly exaggerated vertical scale.)

- A. Initial eruptions are subaqueous with resultant formation of a breccia unit.
- B. Breccias have built up to an elevation above the surface of the water so that basalts are poured out subaerially. On entering the water they may become brecciated, forming the steeply dipping foreset breccias (the giant cross-bedding). Occasional avalanches of breccia fragments down the steep foreset slope may form graded beds at the bottom.
- C. Water completely displaced; eruptions entirely subaerial.
- D. Period of greatest igneous activity is marked by maximum coverage of the Precambrian basement by lavas. Thereafter volcanism wanes and flows reach progressively lesser distances from the source region.
- E. Typical cross-section through a lava patch on Baffin Island produced by dissection and uplift of original lava plateau.

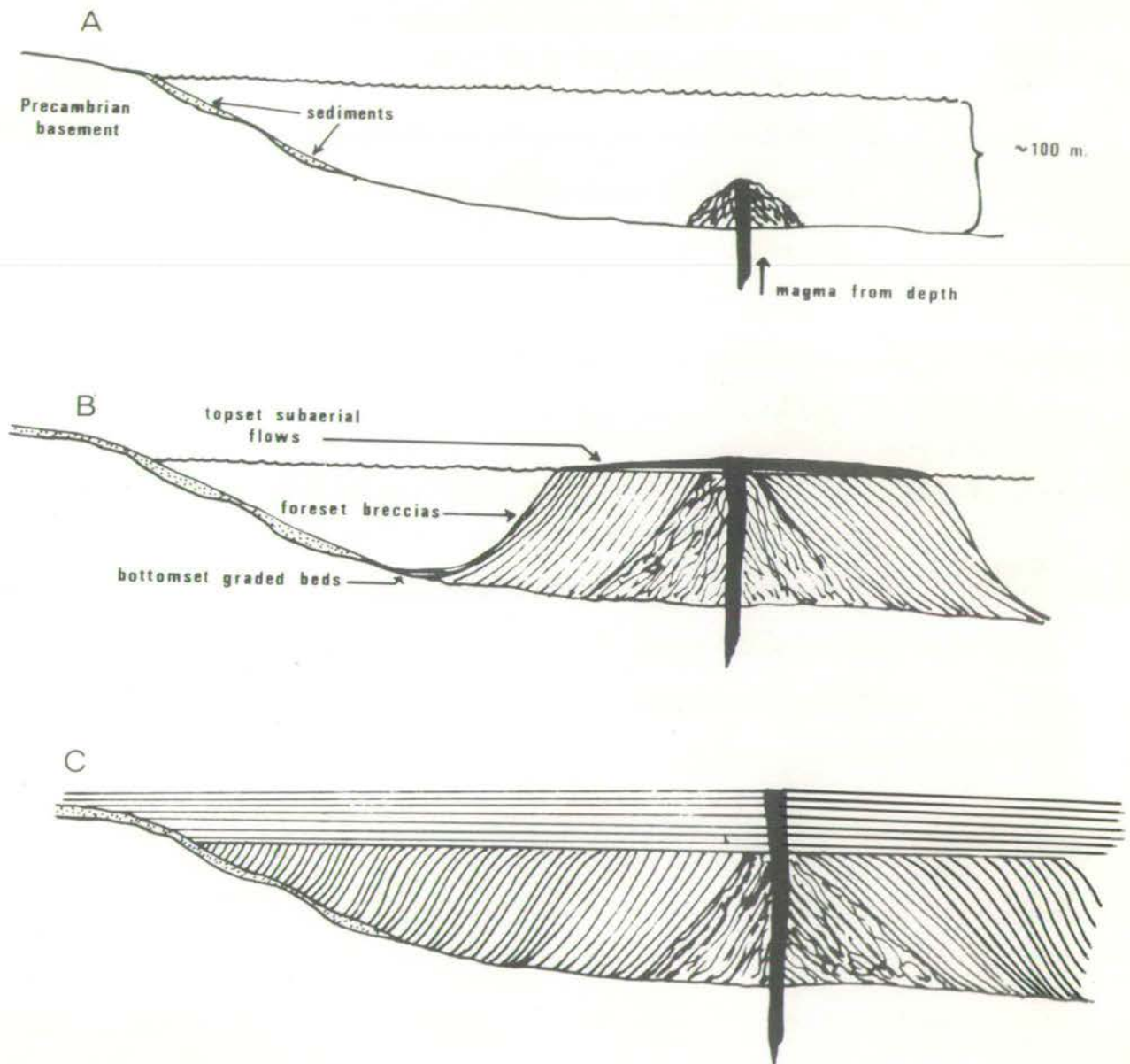


FIG. 2

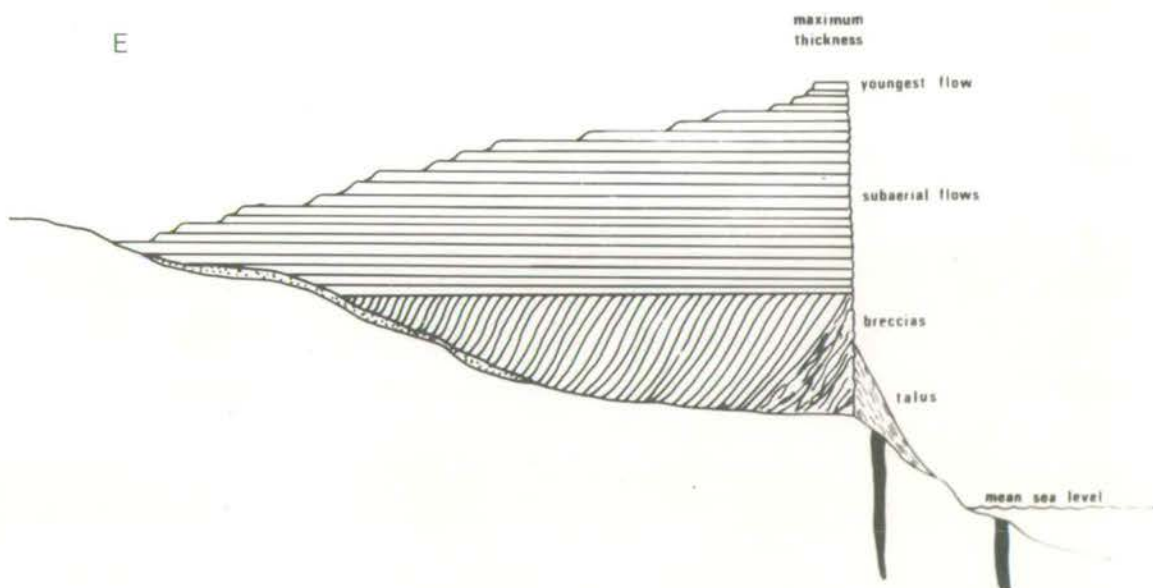
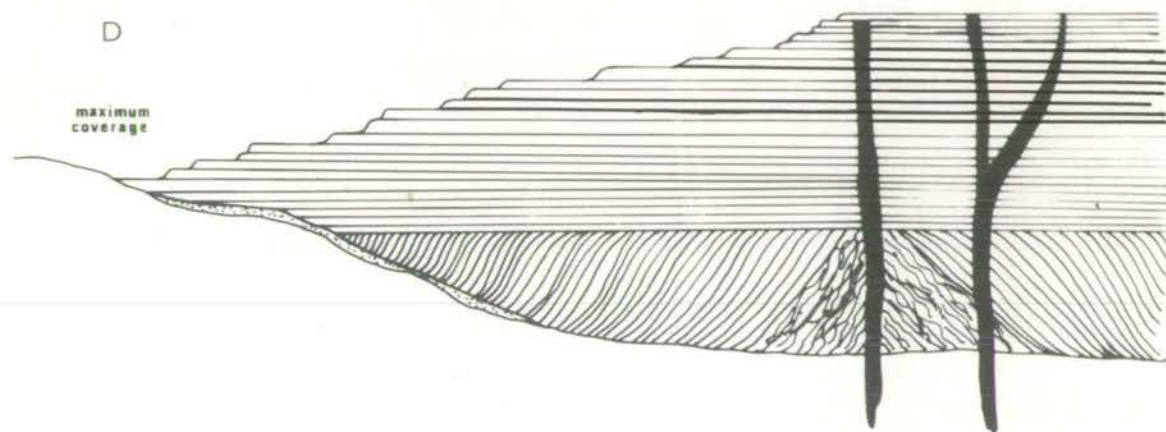


FIG. 2 (cont.)

brecciated unit, it could represent either bottomset beds formed by small avalanches advancing from the steep slopes of the breccia unit, or else the former top of the breccia prior to a later subsidence.

Bonatti (1967) believes that the formation of hyaloclastites is principally due to shattering upon rapid cooling of the sideromelane and can therefore take place at any depth. If true, then in the absence of any other evidence it would be impossible to place a limit on the depth of water into which these basalts were erupted. Fortunately, the problem of depth of water is resolved by the presence of the cross-bedded sequence. From its thickness and attitude it is possible to determine both a minimum for the depth of water into which it was poured and its provenance. The upper orange breccia at Cape Searle with foreset beds 70 m. thick cannot have been erupted into water much deeper than that figure, since both its capping of subaerial flows and its base against the lower black breccia can be seen. No limit can be placed on the depth of water for the black breccia, since its base lies below present sea-level. However, the attitude of the cross-bedding in both units indicates that the source of the volcanics lay to the northeast (Fig. 2 and Plate IV).

(2) Flows

The picritic and olivine-rich flows are characterized by a light-grey weathering surface, and hand specimens are often rather crumbly. As the olivine content decreases, the colour of the flows becomes darker and the cohesion of the rock is much stronger. The average thickness of these flows is less than 5 m.

Structurally these flows may be broken down into four divisions:

a) a lower basal chill a few centimetres thick, often characterized by

vesicles and the presence of tachylite

- b) a massive zone constituting the lower 60% of the flow (but above the basal chill), which is generally featureless except for the occasional development of pipe vesicles and flow banding
- c) a vesicular zone comprising the upper 40% of the flow showing the following features: (i) the vesicles are normally sub-spherical in shape although they are sometimes ellipsoidal, presumably owing to flowage in a viscous magma; (ii) zeolite infillings are common; (iii) in the upper vesicular zone of one flow on Padloping Island, quenching(?) has resulted in the production of spherules of basalt ranging in diameter from 1-10 cm. (sample C-4a; see Appendix A and Plate VII)
- d) the flow tops show the following features: (i) they are often strongly oxidized, as evidenced by the extensive iddingsitization of olivine and the presence of hematite; (ii) they often contain considerable amounts of glass and frequently display ropy (pahoehoe) structures on the upper surface; (iii) some flows which apparently preceded a period of volcanic quiescence have developed a layer of red bole several centimetres thick which has subsequently been baked by the next flow

Correlation of lava flows from one sampling locality to another is impossible, as individual lava flows pinch out laterally over relatively short distances. This indicates that most eruptions were fairly local phenomena, especially those of the later stages. Since individual lava flows lack distinguishing characteristics, the only correlatable stratigraphic features between outcrops are those listed as e), h) and i) above. Thus the general progression from breccias and thick flows to thin flows with oxidized flow tops is recognizable in most localities.

The gradual thinning of the lava flows towards the top of the succession, coupled with the increased oxidation of flow tops, strongly suggests that the intensity of the volcanism waned progressively from start to finish. Although there are no post-volcanic deposits to prove that the complete sequence is still in existence, the lack of glacial erratics on the exposures, together with the characteristic profile (Fig. 2), suggests that these outcrops are virtually complete.

One exception to the observed thinning is a remarkable flow about 70 m. thick forming an outlier near Cape Dyer. The base of this flow, which is approximately 400 m. above the base of the local volcanic section, rests partly on a previous flow and partly on the Precambrian basement. Nothing overlies this thick flow, but judging from the degree of vesiculation the present upper surface very closely approximates the original top of the flow. Six samples have been analyzed from the flow (A-5 and 6; AA-19, 26, 30 and 63) in order to demonstrate the strong degree of differentiation that can take place within thick units. Petrographically (Appendix A) the extreme differentiates would be called troctolite and gabbro on the basis of the mineralogy and very coarse grain size, but there is no evidence that this unit is anything other than a thick lava flow. On the chemically justifiable assumption (see Chapters 3 and 4) that we are dealing with the evolution of one magma batch only in this province, the high fayalite content of the olivines in this flow, (Fa_{19}), suggests that it is one of the youngest on Baffin Island.

(3) Dykes

Basaltic dykes cut the sediments and volcanics only in the north, at Cape Searle and Padloping Island. There are no basaltic dykes to be found in the Precambrian rocks inland from the outcrops. The score, or so, of dykes in

the northern area averaged about 2m. in width; none was thicker than 7 m. and all but one were observed to pinch out before reaching the top of the succession. In general, the dykes are vertical and they strike approximately parallel to the coastline and the line of basalt outcrops. There is nothing particularly noteworthy about the dykes, their mineralogical and chemical composition (C-56, FD-11, FF-41, T-42 and 47) being practically indistinguishable from that of the lava flows.

Carbonatite-like dykes were observed in two localities (Map 1) but in each case were found to cut only the Precambrian basement. Mineralogically, they consist of an olivine-mica-carbonate-graphite assemblage and in the Padloping Island locality are associated with a gossan in the basement rocks. A large number of similar dykes are intimately associated with the Tertiary lavas in west Greenland; so it is possible that those on Baffin Island could also be of Tertiary age.

E) Source of Volcanics

The location of the source area for these volcanics may be established by a process of elimination. There are no recognizable remnants of any central volcanoes in the area; therefore, the source is either offshore or represented by the onshore dykes. However, both the number and width of dykes in the Padloping-Searle area are reckoned too insignificant to have produced even the local succession. The lack of pronounced thermal metamorphism about the dykes renders it unlikely that they were used as conduits for any more than one eruption each. There are no dykes to be found south of Padloping Island and none in the basement rocks inland from the lavas. The southwesterly dip of the giant cross-bedding in the volcanic breccias points to a source north-eastward, at least for the breccias if not the whole succession. Up to a

point, successive lava flows have progressively overlapped southwesterly onto the Precambrian, always maintaining a horizontal attitude. Recent modification of the coast by valley glaciation now obscures the original relations, but it would appear that the first eruptions invaded the floors of flooded valleys and, when the water was displaced, ponded farther into the upper reaches of those valleys. Had the source been on the land, then the first lava flows at least should have had an original dip seaward and may not have ponded anywhere. In addition, there should be evidence of dykes inland, thickening of the section inland and northwesterly dipping, giant cross-bedding in the breccias representing the first subaerial flows to reach the water. It should be noted that the flow which represents the maximum coverage of the land is not the youngest lava flow, the location of which is right at the coast (Fig. 2). Assuming that the wedge-shaped sections of the outcrops are original, the regression of the lava flows from the point of maximum invasion of the land can be taken to reflect the period of gradual waning of activity. These later flows were either not voluminous enough or not fluid enough to achieve the coverage of earlier flows.

If it is argued that erosion is responsible for the present shape of the cross-sections through the outcrops and that the last flow did extend farthest inland, then the thinning and reddening of successively later flows could be due to broadening of the original valleys, thereby forcing constant volumes of magma to cover ever-increasing areas. Here, it would have to be argued that either activity came to an abrupt halt or else erosion had also obscured the regressive pattern.

The only way in which the combination of scarcity of dykes, orientation of cross-bedding and attitude of flows can be explained is by appealing to a source area situated to the northeast of the present line of outcrops. So far

a model for the origin of the Baffin Island basalts only requires that the source area be offshore and that the first eruptions should be subaqueous. Further development of the model is deferred until the field relations in west Greenland have been discussed.

II. West Greenland

A) General

The Precambrian geology in the vicinity of the west Greenland basalt province has been described by Escher and Burri (1967), Henderson and Pulvertaft (1967) and Escher and Pulvertaft (1968). In general, the region is a structural complex of gneisses and metasediments with greenschist, amphibolite and granulite metamorphic facies represented. Around Svartenhuk in particular, there are frequent occurrences of garnetiferous gneisses, tourmaline-bearing pegmatites and rusty-weathering gossans.

The pre-volcanic Cretaceous and Lower Palaeocene (Danian) history of west Greenland is characterized by almost continuous sedimentation in a relatively small basin controlled by repeated normal faulting (Rosenkrantz and Pulvertaft, in press). The sediments appear to have been derived from a large part of the interior of Greenland, now covered by the inland ice (Koch, 1964), but in some cases the provenance of the sediments is demonstrably very local and to the east. In general, the southern half of the basin (Disko and S. Nugssuak) was characterized by predominantly limnic and fluviatile deposits occasionally interrupted by marine invasions, whereas the northern sector (N. Nugssuak and Svartenhuk) experienced an almost continuous sequence of marine deposits throughout the Senonian. Palaeontological evidence has shown that the affinities of the marine fauna became less North American and progressively more European during the Upper Cretaceous. Rosenkrantz (in

Rosenkrantz et al., 1942, p. 41) says of the Upper Santonian that there "seems to have been a connection as far as with the Coloradoan Sea, but at the same time the Inoceramus show that a new marine connection has been opened in a southern direction through Davis Strait to the North European Senonian Sea." This conclusion has been supported by more recent work on the ammonite fossils (Birkelund, 1965).

The main events of the Cretaceous and early Tertiary are summarized in Table 1, and a general geological map of the west Greenland province is given in Fig. 3. Correlation between, and exact stratigraphical placing of, the non-marine formations is still not possible (Koch, 1963, 1964) but the general framework is known. It can also be seen from the table that the olivine-rich basalts of west Greenland were erupted into topographic lows which had been the former sites of marine sedimentation, while areas at higher elevation still received subaerial deposits of the Upper Atanikerdluk Formation. The later extensive eruption of feldspar-phyric basalts covered the earlier picrites and some areas of terrestrial sediments which had not previously received any lava flows.

As Svartenhuk Peninsula is believed to present the most complete section of volcanics and was the area directly investigated by the author, a short description of the field relations now follows. For convenience the description has been broken down into a north and a south region along a line running roughly from Itsako on the east coast to Svartenhavn on the west. Fig. 4 gives sampling localities and place names referred to in the following description, and the detailed geological map of Svartenhuk (Map 2) is in the pocket.

B) Southern Svartenhuk

The east coast of Svartenhuk from Maniserqut to Firefjeld and then along

Table 1. Stratigraphic Correlation in Baffin Bay.

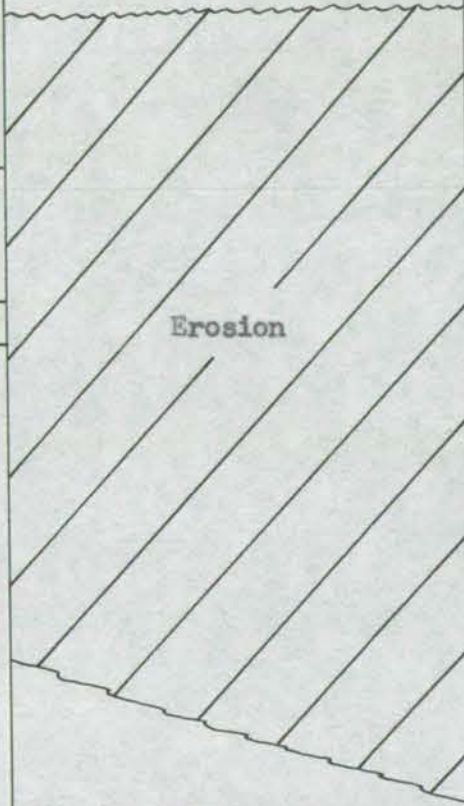
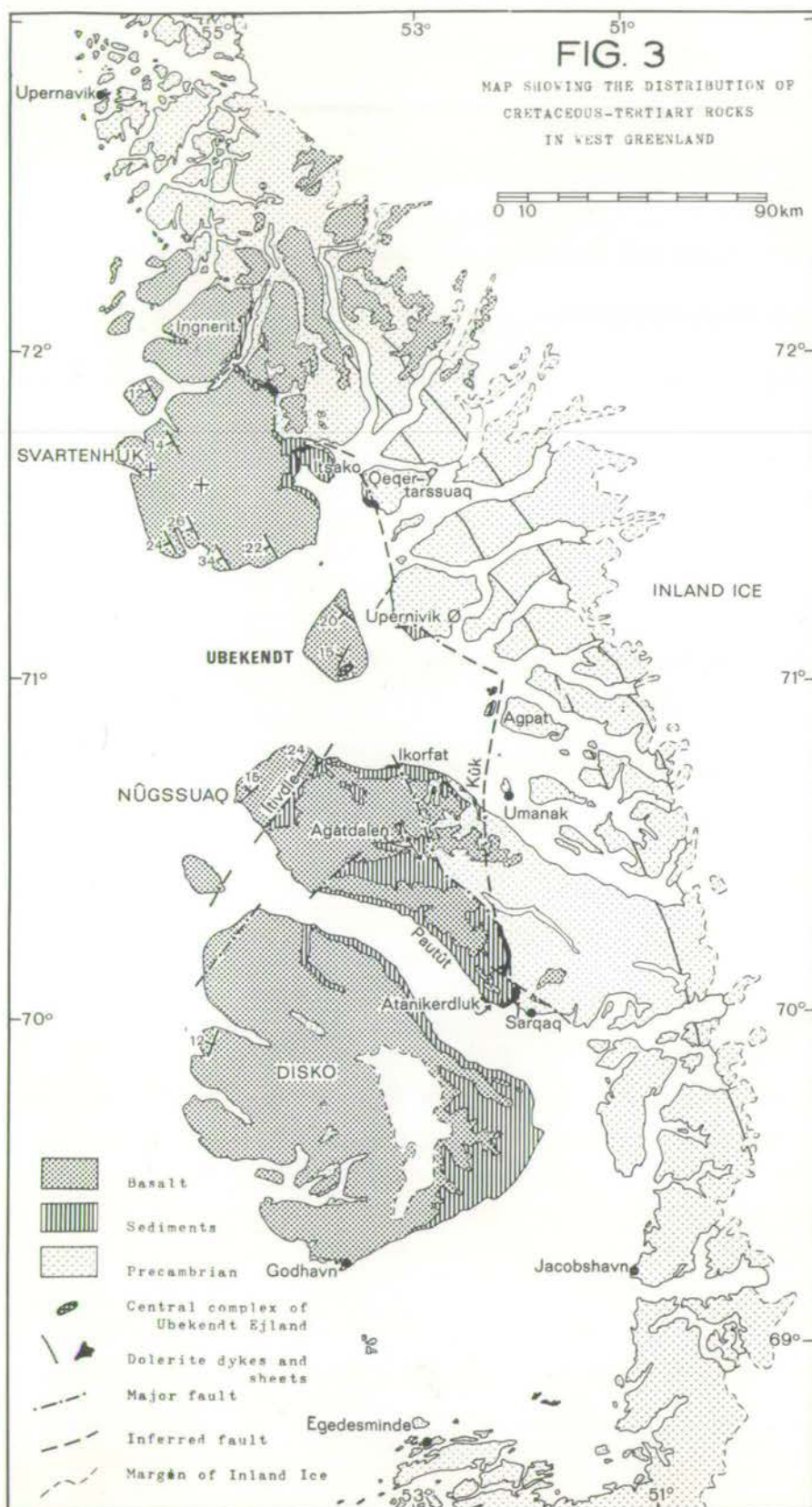
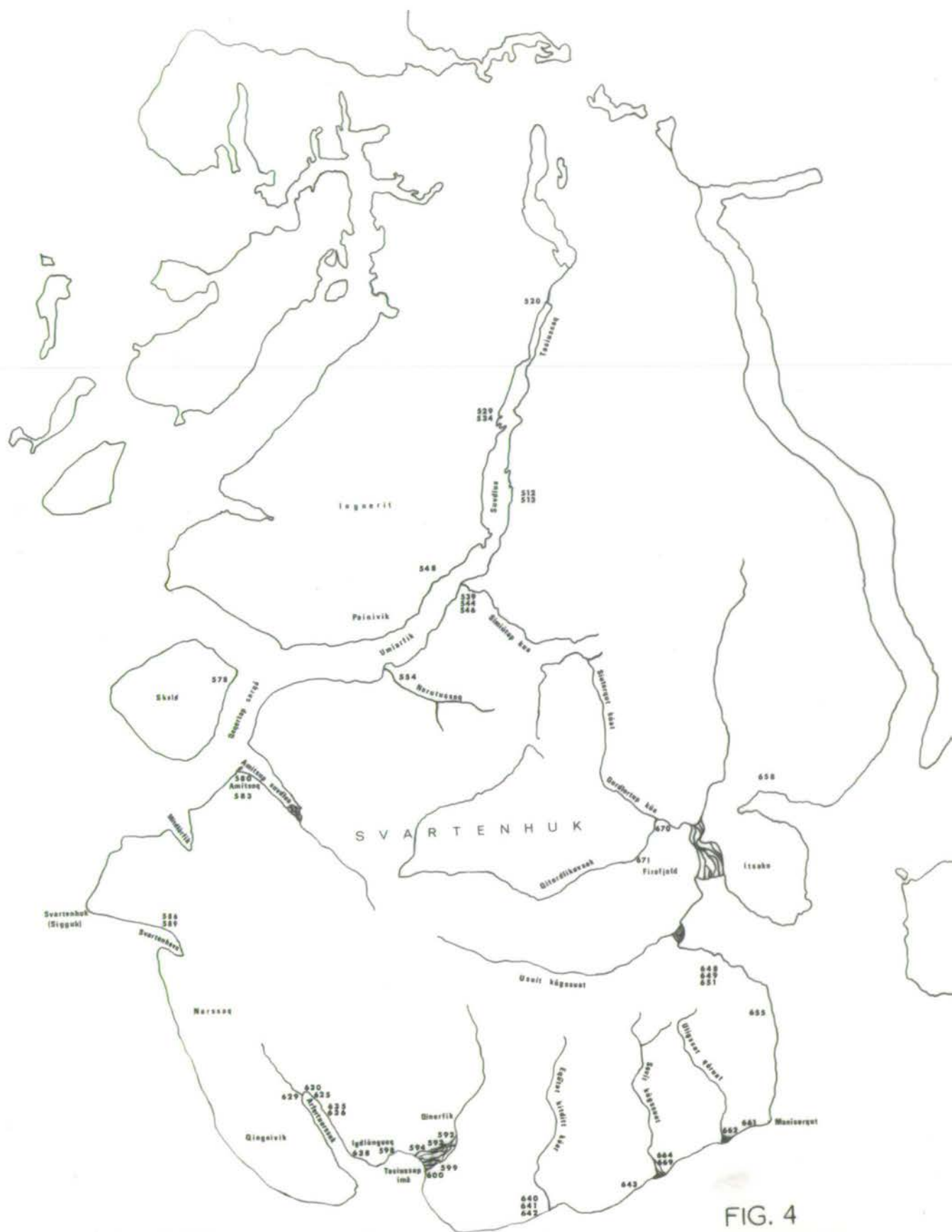
Age	Disko	Southern Nugssuak	Composite Northern Nugssuak	Itsako	Composite Svartenhuk	Baffin Island
<u>LOWER PALAEOCENE</u>						
Upper Danian	Feldspar-phyric Basalts Olivine Basalts(?) Upper Atanikerdluk Fm. ↑	Feldspar-phyric Basalts Upper Atanikerdluk Fm. Agatdal Marine Shales Upper Atanikerdluk Fm.	Feldspar-phyric Basalts Olivine Basalts Basal Basalt Breccia Agatdal Marine Shales	Upper Atanikerdluk Fm.	Feldspar-phyric Basalts Intra-basaltic Sediments Olivine Basalts Basal Basalt Breccia	Olivine Basalts Basal Basalt Breccia Terrestrial Sediments (= Upper Atanikerdluk Fm.?)
		Unconformity				
Lower Danian		Kangilia Marine Shale with Tuffs Basal Conglomerate	Kangilia Marine Shale with Tuffs Thick Basal Conglomerate	Tuffs Thick Sandstone		
		Unconformity				
<u>UPPER CRETACEOUS</u>						
Senonian { Maastrichtian Campanian Santonian Coniacian Turonian Cenomanian	Atane Fm.	Limnic-Fluviatile Sediments (Atane Fm.)	} Nearly Continuous Marine Sedimentation			
		Marine Fm.		<u>Haploscaphtes</u> (European)		
		Limnic-Fluviatile Sediments (Atane Fm.)	<u>Inoceramus steenstrupi</u> (Transitional to European)	} Marine Shale		
		Marine Fm.				
		Limnic-Fluviatile Sediments of Kome Type (Pautut Fm.?)	Limnic-Fluviatile Sediments of Kome Type	Limnic-Fluviatile Sediments of Kome Type		Marine Shales <u>Scaphites ventricosus</u> (Coloradoan)
<u>LOWER CRETACEOUS</u>			Unconformity			
			Kome Fm.	Kome Fm.		
U N C O N F O R M I T Y						
<u>PRECAMBRIAN</u>	Nagssutoqidian Fold Belt 1650-1790 my.					Churchill Province 1610-1790 my.

Fig. 3. General Geology of the West Greenland Basalt Province (after Rosenkrantz and Pulvertaft, in press).

Fig. 4. Place Names and Location of Analyzed Samples in Svartenhuk Peninsula, West Greenland.





the west bank of Siutergut kuat is dominated by the basalt breccia formation which is described in detail by Munck (in Rosenkrantz et al., 1942). The breccias rest on an eroded base of marine sediments varying in age from Upper Turonian to at least Coniacian and possibly higher. The greatest thickness of breccia, approximately 300 m. in the river bed northwest of Firefjeld, can be correlated with the deepest level of erosion into the Cretaceous. The subaqueous origin of the breccia is proven by the development of giant cross-bedding, and the existence of intercalated marine shales indicates a shallow sea environment. The dip direction of the cross-bedding is locally erratic but in the main it is northeasterly, thereby suggesting provenance from the southwest. Two types of breccia can again be defined on the basis of colour, reddish brown and black, and this feature suggests affinities with the orange and black varieties of Cape Searle, Baffin Island. Unfortunately, many of the important contact relations, as well as original attitudes of the formations, have been obliterated by landslips of the overlying breccia and basalt flows onto the unstable marine shales.

The south coast proper of Svartenhuk runs perpendicular to the regional strike of the subaerial lava flows. Landings were made at several places along the coast but no continuous traverse on foot was made. All flows were of grey-weathering olivine-rich basalt and averaged 3-5 m. in thickness. The dip on the lava flows varied from $12-37^{\circ}$ to the southwest, and the section appeared to be continuous except for very minor normal faults involving downward displacements of a few metres on the eastern blocks. If there is no major repetition of the sequence along the coast, then the lava pile must be approximately 8-10 km. thick. The absence of a linear increase in certain trace elements (see Chapter 3) from east to west along this coast suggests that there may be some substantial repetitions in the stratigraphic sequence.

The faults responsible may exist undetected in the three prominent river valleys which reach the coast - Uliqssat qoruat, Savit kugssuat and Equatat kitditt kuat.

A fault has already been suggested by Clarke (1966 field report, G.G.U.) in the unnamed valley running northeast from Tasiussap ima. The reasoning behind this prediction is that the section of coast from Equatat kitditt kuat westwards consists entirely of the picrites and olivine basalts characteristic of early eruptions, whereas north of the valley in question there is a rapid transition of the olivine basalts southwestwards into feldspar-phyric basalts. Thus at Tasiussap ima feldspar-phyric basalts on the north shore are "on strike" with picritic basalts on the south shore. If the movement along a fault between the two areas is of a transcurrent nature and later than the regional tilting, then the southern block has moved relatively west. If the predominant motion has been vertical and subsequent to the regional tilting, then the south block has moved relatively upwards. If the previous suggestion about faulting along the south coast is true, then the block between Equatat kitditt kuat and the unnamed valley to the west must be a horst.

On a traverse from Qinerfik in the unnamed valley to Igdlunguaq on Arfertuarssuk the critical change from picrites through olivine-poor basalts to feldspar-phyric basalts can be observed. At the head of Arfertuarssuk outcrops of trachyte occur, one intrusive (?) and the other extrusive, judging from the degree of vesiculation. These compositions represent the end of chemical evolution in this province, and therefore the sequence of feldspar-phyric basalts of Narssaq and Qingnivik to the west may represent yet another up-thrown block. This faulting would repeat the stratigraphy observed over a comparable thickness east of Arfertuarssuk, and would extend to either Svartenhavn or Mitdlorvik or both.

C) Northern Svartenhuk

The general section found in the north of Svartenhuk Peninsula is a much attenuated version of the sequence exposed in the south. In Umiarfik-Suvdlua-Tasiussaq Fjord the picrites do not attain thicknesses of greater than 1 km., and the west side of the Fjord has considerably less than that.

The Precambrian basement rises from south to north, first outcropping near Simiutap kua, and continues to rise until at the head of Tasiussaq it has reached about 400 m. The nature of this basement surface has been very important in the distribution of pre-volcanic sediments and the basalts themselves. The sediments necessarily collected in the topographic lows and tended to even out the surface that was subsequently to receive the breccias and subaerial flows. The general stratigraphic sequence in the north is as follows: Precambrian basement - sediments - olivine-rich breccias - subaerial picrites - intra-basaltic terrestrial sediments - feldspar-phyric breccias - feldspar-phyric subaerial flows. Description of this sequence is most conveniently broken down into the following areas:

- (1) West side of Umiarfik-Suvdlua-Tasiussaq
- (2) East side of Qeqertap sarqa-Umiarfik-Suvdlua-Tasiussaq
- (1) West side of Umiarfik-Suvdlua-Tasiussaq (Fig. 5A)

The section on the west side of this Fjord is for the most part flat-lying except near Painivik, where a gentle southwesterly dip is observed (Fig. 5A). In a northerly direction the olivine-rich breccias of the lower series of volcanics eventually give way to an approximately equivalent thickness of sediments, for which the depositional environment is unknown. These sediments in turn give way to the Precambrian basement, and the subaerial picritic lava flows overlap all three previously mentioned formations. This lower lava group is overlain by a thin veneer of terrestrial sediments upon

Fig. 5. Shoreline Geology of Umiarfik-Suvdlua-Tasiussaq.

A. West side, looking east.

B. East side, looking east.

Ornament as Map 2.

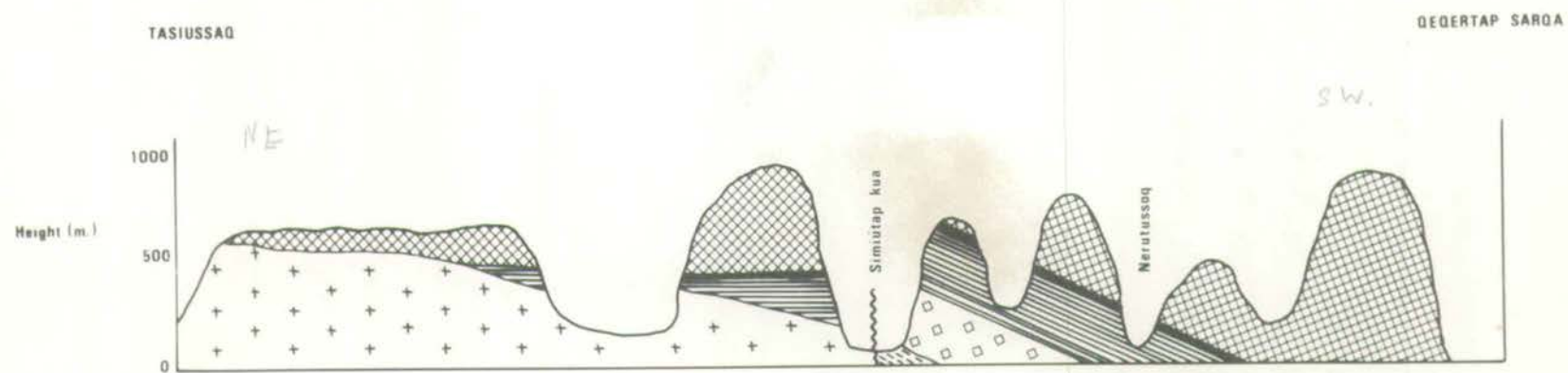
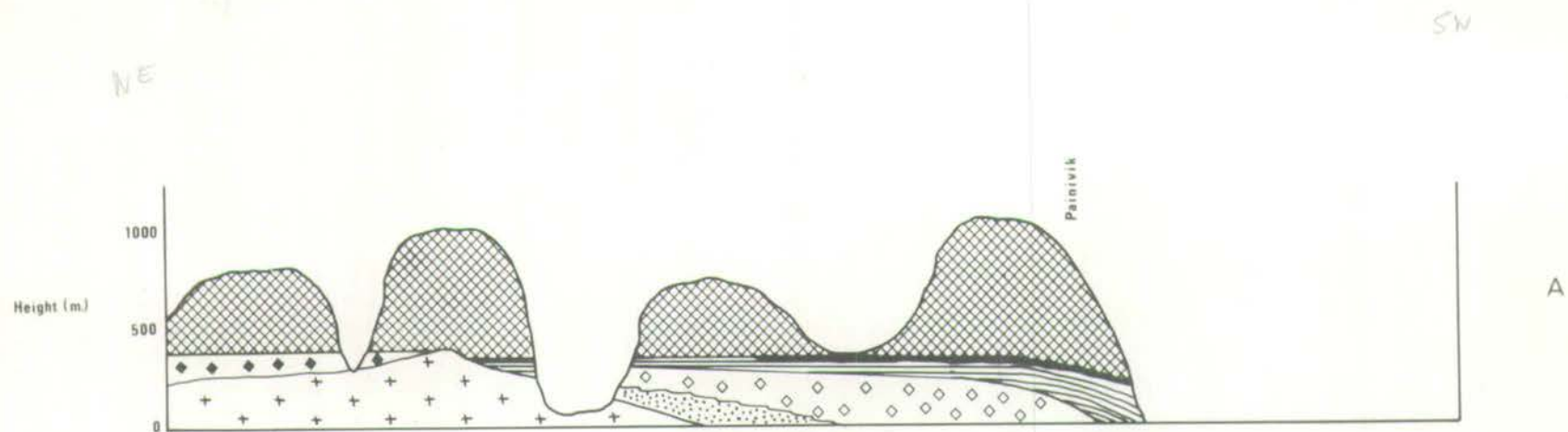


FIG. 5

which lie up to 800 m. of mainly thick feldspar-phyric basalts with minor intercalated olivine basalt flow groups. The typical feldspar-phyric lava flow differs from an olivine basalt flow in being thicker (average approx. 25 m.), brown-weathering and more resistant to erosion. These flows display essentially the same structural divisions as a typical picritic flow, with the following differences: (i) columnar jointing is frequently developed; (ii) flows are more massive, development of vesicles is reduced and amygdale minerals tend to be silica rather than zeolite; (iii) flow tops without red bole are extremely rare, suggesting that the frequency of eruption was less than for the olivine basalts.

The section in Tasiussaq is remarkable for its complete lack of the lower basalt series, which had been effectively blocked from extending farther north by the rising Precambrian topography. Consequently, the initial volcanic member in this area is a feldspar-phyric basalt breccia, which extends along the entire west coast at an elevation of approximately 500 m. It apparently rests on the Precambrian basement, but talus slopes probably obscure a veneer of water-laid sediments between the basement and volcanic rocks. It is worthy of note that there are virtually no feeder dykes this far inland.

(2) East side of Umiarfik-Suvdlua-Tasiussaq (Fig. 5B)

From Simiutap kua northwards the section is more or less identical to that on the west side, except that in Tasiussaq the feldspar-phyric basalt breccia is absent because the Precambrian basement rises to a greater height. Therefore, the first volcanic activity inland was eruption of subaerial feldspar-phyric basalt flows.

The valley of Simiutap kua marks a zone of considerable faulting, the southern block having been tilted in a southwesterly direction, and as a result a considerable thickness of picritic breccia has been exposed. Since

the basement rocks do not outcrop on the south side of the river in spite of this relative uplift, it must be deduced that a considerable drop in the level of the basement terrain existed in pre-volcanic times. This drop may be part of the earlier, major Cretaceous fault zone (Koch, 1929), on which the movement has been reversed, or it may only be another indication of the considerable pre-Tertiary relief in west Greenland. Whatever the reason for the plunge in the level of the Precambrian, this depression does account for the enormous thickness of picrite breccia developed only to the south of the valley. Because of the multiplicity of faults and slumps it is difficult to estimate the thickness of the breccia, but it must be approximately 500 m. The cross-bedding within the breccias renders difficult an estimate of their true dip; however, the overlying picritic flows have southwesterly dips of $5-10^{\circ}$. Both formations are cut by hundreds of dykes, mainly of olivine-rich basalt but occasionally of feldspar-phyric varieties.

At Nerutussoq, the picritic sequence is well exposed on the north side of the valley and dips below a great thickness of feldspar-phyric flows on the south side. Here too the contact between the two lava types is marked by a thin band of sandstones, pebble conglomerates and minor breccia.

Southwest from Nerutussoq the lava series consists essentially of feldspar-phyric flows with minor outpourings of thin, grey-weathering olivine basalt flows. The southwesterly dip becomes less pronounced until at Svartenhuk (Sigguk) the flows are horizontal.

Skalø and the west coast of Ignerit appear to be composed entirely of feldspar-phyric basalt flows.

D) Geological History of Svartenhuk

Prior to the commencement of volcanic activity, southern Svartenhuk was

undergoing erosion of its marine Cretaceous sediments, and the north was experiencing simultaneous erosion of topographic highs in the Precambrian rocks and deposition of the material in river valleys and lakes. Given the thick sequence of breccia in the south, it would seem necessary to invoke a strong, local marine invasion of the south. This may have been achieved by subsidence of the main block of Svartenhuk along a fault defined by Simiutap kua - Siuterqut kuat - Qordlortup kua. The giant cross-bedding in the breccias formed by the first eruptions indicates a southwesterly source for these rocks. Varying thicknesses of breccia accumulated, depending mainly on the depth of the water, the south receiving consistently more than the north.

Once the water was displaced, subaerial extrusions began. Again the southern half of the peninsula tended to be the site of the greatest activity, apparently developing enormous thicknesses of picritic lava flows, whereas only the more voluminous of these lavas appear to have reached the north. Potential feeder dykes are rare north of Simiutap kua, whereas the south coast is cut by a very dense network of dykes that may have acted as feeders.

Volcanic activity apparently continued uninterruptedly in the south from picritic breccia to picritic flows, followed by olivine-poor basalts and later feldspar-phyric basalts. Finally, and possibly after only a short interval, trachytes were erupted. By way of contrast, the north experienced a small but significant break in the volcanic sequence between the picrites and the feldspar-phyric basalts, within which terrestrial sediments were deposited.

The number of dykes of feldspar-phyric composition on Svartenhuk does not seem to be in proportion to the huge volume of the lavas, when compared with the number of dykes associated with the picrites. Their absence inland also seems to point to an offshore source for this material. The feldspar-

phyric flows themselves are remarkable for their constant thickness and widespread extent, each flow being traceable for many kilometres. As a collective unit they cover a larger area than do the picrites in the west Greenland province and thus extend to regions such as Disko, which may not have previously received any lavas.

The apparent absence of unconformities in the basalts suggests that it was some time after the close of the feldspar-phyric basalt stage that the peninsula became tectonically unstable and was tilted seaward. Its major displacement appears to have been about a northwest-southeast axis roughly bisecting the peninsula, so that while uplift occurred along the north, the south coast was dropped down. Accompanying this general rotation there have been numerous smaller, near-vertical adjustments which may have had the effect of producing repetition in the sequence along the south coast. Some of the other fractured areas have provided avenues for the carbonatite-like dykes, but it is not proposed to discuss these further.

III. Relationship between the Two Volcanic Provinces

The last three columns of Table 1 allow a direct comparison to be made between the early Tertiary events of Itsako, Svartenhuk and Baffin Island respectively. This information, combined with the detailed descriptions of field relations in the preceding sections, illustrates the strong degree of similarity in the geological evolution of these two areas. If only one of the lava provinces existed in Baffin Bay, then it would be easy to propose that the source area of the volcanics has either simply been eroded away or else faulted beneath present sea-level. However, given the established similarities between southwest Greenland and Labrador (see Chapter 5) and the possible existence of a mid-oceanic ridge in Baffin Bay-Davis Strait

(Godby et al., 1966), it then becomes difficult to imagine a parallel but independent evolution of the two basalt provinces.

A model is now presented for the creation of the two, near mirror-image basalt provinces, striving to satisfy the following observations:

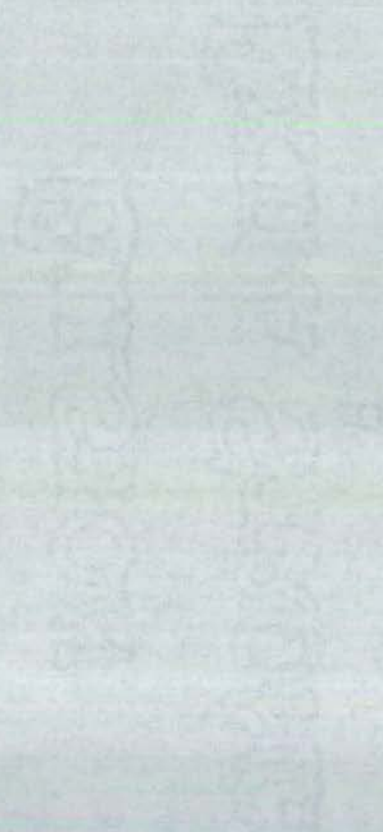
- 1) the general stratigraphic parallelism between the Cape Dyer area of Baffin Island and Svartenhuk in the Upper Cretaceous-Lower Tertiary (except for the absence of marine sediments and feldspar-phyric basalts in Baffin Island)
- 2) the distribution of sediments and breccias on Baffin Island
- 3) apparent derivation of volcanics from seaward in both areas
- 4) scarcity of dykes on Baffin Island
- 5) relatively early waning of volcanic activity on Baffin Island
- 6) continuous evolution of the feldspar-phyric basalts from the olivine basalts in the south of Svartenhuk only; eruptive break in the north
- 7) development of a regional dip in Svartenhuk

As may be seen from Fig. 6, the model appeals to convective overturn in the mantle to separate what had formerly been a single cratonic block. It will only be after the presentation of the chemical, petrological, geophysical and regional geological considerations in succeeding chapters that the suitability of a continental drift model can be evaluated. For convenience the sequence of events is divided into five arbitrary phases.

A) Phase I

- 1) Zone of weakness in the crust develops into a rift valley, possibly related to diverging limbs of a convection cell in the mantle.
- 2) Deposition of terrestrial sediments occurs in fluvial and lacustrine

Fig. 6. Model for the Opening of Baffin Bay based on Field Relations. For explanation, see text.



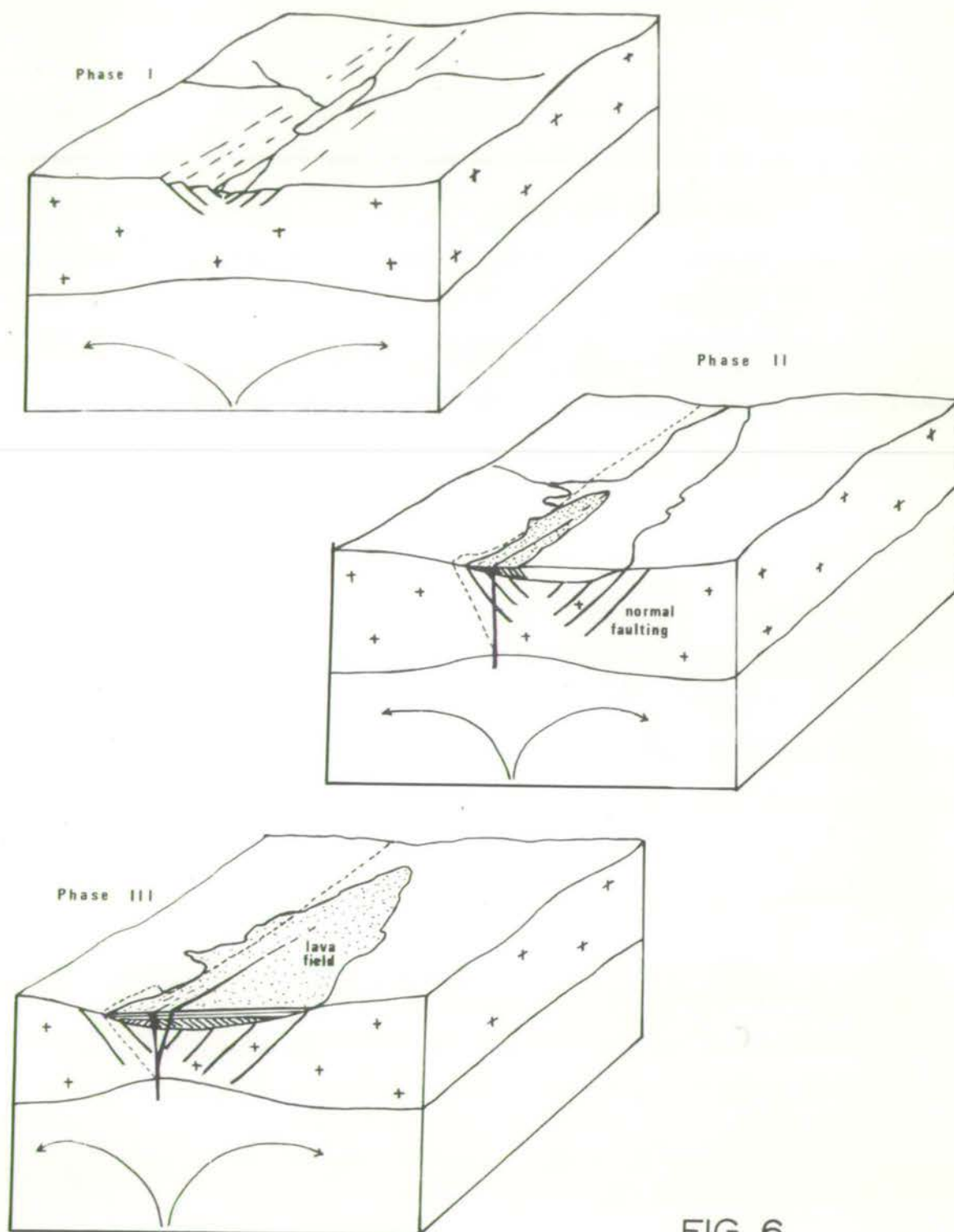


FIG. 6

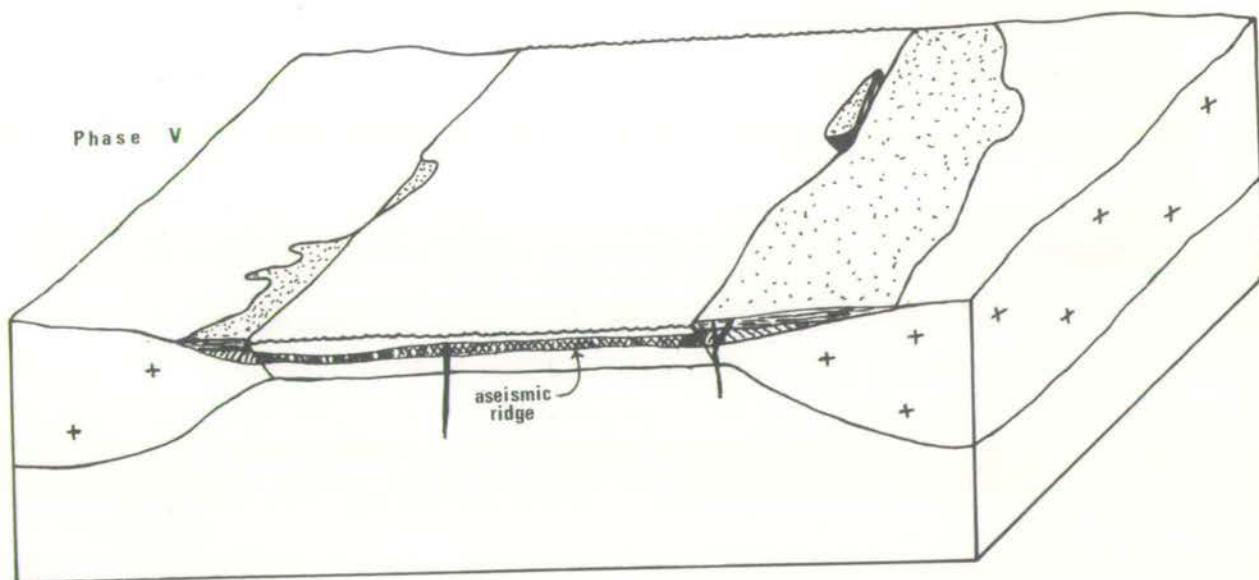
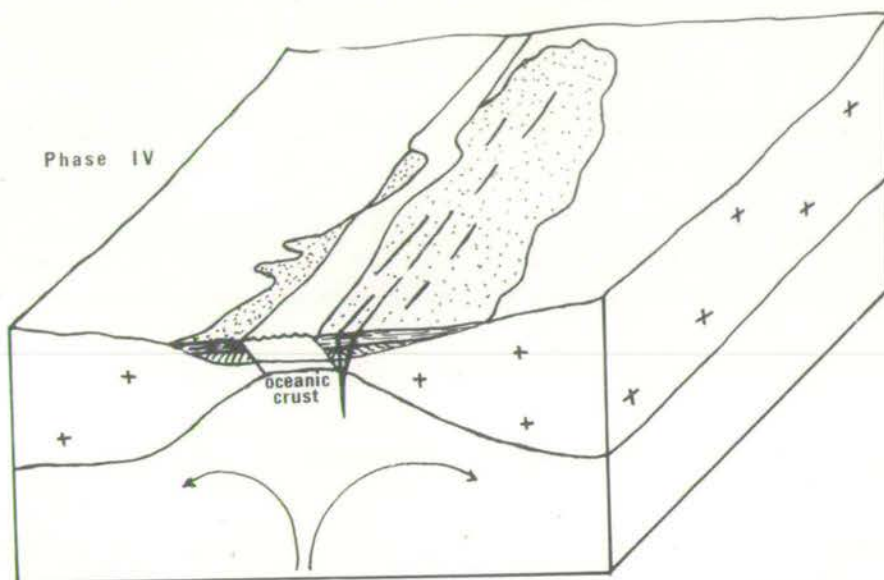


FIG. 6 (cont.)

environments associated with the rift valley.

B) Phase II

- 3) Crustal necking is achieved by plastic flow and conjugate normal faulting in the sialic crust.
- 4) Subsidence in the axial trough is followed by invasion by the sea with subsequent drowning of river valleys and initiation of marine sedimentation.
- 5) During a later subsidence the first eruption of volcanic material (breccias) occurred on the southwest side of the rift valley (the location being suggested by chemical considerations, see Chapters 3, 4).
- 6) Marine sedimentation continues on the northeast side of the valley with occasional deposition of tuffaceous material derived from the activity to the southwest.
- 7) Note that the area which is eventually to become the southern end of the Baffin province around Cape Dyer is practically devoid of sediments and breccias, whereas the northern end (Padloping-Cape Searle area) has an abundance of both.

C) Phase III

- 8) Voluminous outpourings of breccia and subaerial basalts take place to the temporary exclusion of the sea. Stratigraphic equivalents on opposite sides of the rift are not necessarily time equivalents. They could have been erupted later, in which case they may show a different degree of chemical evolution.

D) Phase IV

- 9) Tensional stresses continue with the eventual severing of the continuous

continental crust along one of the former sets of normal faults of the rift valley. This fault plane or zone extended from the base of the crust at the main zone of crustal thinning to a point on the surface slightly to the southwest of the principal volcanic activity.

- 10) Formation of new oceanic crust begins.
- 11) The source area of the Baffin Island volcanics is carried away on the Greenland block, and therefore volcanic activity is seen to wane on the southwest side of the valley. Volcanism continues unabated on the northeast side.
- 12) West Greenland lava field is now greatly extended by the eruption of the feldspar-phyric basalts. This activity appears to have been continuous in the south, is separated from the earlier olivine basalts by a brief period of sedimentation in the north, and is nowhere represented on the now remote Baffin Island block.

E) Phase V

- 13) Volcanic activity declines in west Greenland as magma source becomes depleted.
- 14) Pressure release as a result of continental rupture provides a new locus of volcanic activity along the axis of the rift. Although there is no subaerial manifestation of this, the activity was apparently sufficient to fill the tension cracks produced by the drifting apart of the continental blocks and, in the "wake" of the terrestrial basalts, to produce an aseismic ridge such as those extending out from Iceland towards east Greenland and Scotland (Wyville-Thomson ridge).
- 15) Collapse of part of the west Greenland province occurs as support is withdrawn.

This model is in accordance with the list of observations which required explanation. In particular, the apparent derivation of volcanics from seaward in both provinces is satisfied, although if the base of the section in the southwestern reaches of Svartenhuk could be observed, a reversal of this direction of provenance might be seen to occur (Fig. 6 IV, V).

I. Introduction

In Table 2, a total of 81 new analyses of Tertiary lavas from Baffin Island (37) and Svartenhuk Peninsula (44) are presented. These are accompanied by brief petrographic descriptions in Appendix A. Short descriptions of analytical procedures as well as information on accuracy and reproducibility are contained in Appendix B. Data processing into norms, discriminant functions and principal components was done on an Atlas computer.

The letter, or first letter where there are more than one, in the Baffin Island sample-names corresponds with the sampling localities on Map 1 (in pocket). The sample numbers for the west Greenland specimens are abbreviations of a systematized G.G.U. collection, and each should be preceded by "87" in order to obtain the complete number; e.g. sample 629 is equivalent to G.G.U. 87629. The analyses in Table 2 are arranged in the original alphabetical or numerical order of collection. Major elements and normative constituents are presented in weight per cent., and trace elements in parts per million.

A few remarks on the sampling procedure should be made. First, it may be noted that 10 of the 81 rocks analyzed are represented by samples of loose blocks. It was felt that this method of obtaining material was justified when outcrops were inaccessible or when samples of comparable freshness or composition to those represented by talus or boulders could not be located in situ. It was considered preferable to obtain samples by this means than to risk the implication of compositional gaps which might not exist. Normally, samples were taken from the lower massive portion of lava flows in order to avoid the possible oxidation and contamination effects associated with the

	<u>A-5</u>	<u>A-6</u>	<u>AA-19</u>	<u>AA-26</u>	<u>AA-30</u>	<u>AA-63</u>
SiO ₂	43.7	47.8	51.1	43.8	43.0	49.6
TiO ₂	0.38	0.68	1.21	0.54	0.45	1.01
Al ₂ O ₃	8.1	16.7	14.8	7.4	7.0	14.3
Cr ₂ O ₃	0.35	0.10	0.15	0.41	0.42	0.17
Fe ₂ O ₃	2.3	1.7	1.6	1.9	1.5	2.3
FeO	10.4	6.5	5.9	9.4	9.6	5.9
MnO	0.20	0.14	0.14	0.24	0.19	0.16
MgO	26.3	11.2	8.5	28.1	28.8	8.7
NiO	0.18	0.04	0.02	0.20	0.21	0.01
CaO	6.4	12.1	14.3	6.3	5.9	14.7
Na ₂ O	0.89	1.52	2.01	0.85	0.65	1.68
K ₂ O	0.04	0.09	0.13	0.06	0.08	0.12
P ₂ O ₅	0.03	0.06	0.11	0.06	0.06	0.10
H ₂ O ⁺	0.94	1.23	0.44	0.54	1.78	0.80
TOTAL	100.2	99.9	100.4	99.8	99.6	99.6
Ba	62	72	61	58	65	84
Cu	68	105	100	59	67	151
Ga	9	20	20	8	8	17
Rb	1	2	2	1	1	3
Sr	79	149	156	76	74	131
Y	7	17	18	14	10	22
Zn	68	38	43	56	60	39
Zr	34	50	74	42	38	60
Qz	-	-	0.85	-	-	0.73
Or	0.24	0.54	0.77	0.36	0.48	0.72
Ab	7.60	13.06	17.02	7.25	5.62	14.41
An	18.09	39.06	31.00	16.38	16.24	31.47
Di	10.95	17.06	31.33	11.70	10.39	33.37
Hy	9.72	16.80	13.90	8.65	9.88	13.56
Ol	48.76	9.35	-	51.16	53.50	-
Mt	3.32	2.53	2.35	2.72	2.24	3.31
Ch	0.52	0.15	0.22	0.61	0.63	0.25
Il	0.73	1.31	2.30	1.03	0.87	1.94
Ap	0.07	0.14	0.26	0.14	0.15	0.24

	<u>C-4a</u>	<u>C-15</u>	<u>C-25b</u>	<u>C-56</u>	<u>DX-9</u>	<u>DX-18</u>
SiO ₂	42.7	44.5	45.2	47.4	47.9	46.5
TiO ₂	0.53	0.52	0.80	0.64	1.03	0.89
Al ₂ O ₃	7.6	7.7	11.3	13.6	13.6	13.1
Cr ₂ O ₃	0.40	0.36	0.25	0.14	0.14	0.17
Fe ₂ O ₃	2.5	2.2	2.3	3.2	4.9	3.0
FeO	7.9	8.7	8.2	7.0	5.8	7.5
MnO	0.18	0.19	0.18	0.17	0.18	0.17
MgO	27.8	28.3	19.4	12.7	12.9	13.8
NiO	0.22	0.22	0.12	0.05	0.05	0.05
CaO	6.7	6.5	9.1	12.1	11.3	10.1
Na ₂ O	0.64	0.85	1.06	1.39	1.28	1.64
K ₂ O	0.05	0.06	0.04	0.02	0.11	0.07
P ₂ O ₅	0.07	0.06	0.08	0.05	0.11	0.09
H ₂ O+	2.68	0.81	2.04	1.41	0.60	2.76
TOTAL	100.0	101.0	100.1	99.9	99.9	99.8
Ba	36	36	45	32	104	69
Cu	94	81	113	151	91	115
Ga	10	10	14	17	17	16
Rb	1	1	1	1	1	1
Sr	141	67	92	62	148	123
Y	12	16	21	18	21	19
Zn	60	58	60	56	60	68
Zr	42	44	56	48	76	68
Qz	-	-	-	-	-	-
Or	0.30	0.35	0.24	0.12	0.66	0.43
Ab	5.57	7.20	9.17	11.95	10.93	14.30
An	18.30	16.97	26.59	31.17	31.20	28.99
Di	12.00	11.62	14.96	23.50	19.43	17.63
Hy	10.04	10.76	16.04	17.79	27.92	18.24
Ol	48.26	48.28	27.52	9.23	0.31	13.76
Mt	3.71	3.16	3.35	4.66	7.10	4.44
Ch	0.61	0.53	0.38	0.21	0.21	0.26
Il	1.04	0.99	1.55	1.24	1.97	1.74
Ap	0.17	0.14	0.19	0.12	0.26	0.22

	<u>DX-24</u>	<u>DX-31</u>	<u>DX-48</u>	<u>DX-52</u>	<u>E-2</u>	<u>FD-11</u>
SiO ₂	46.0	44.3	47.3	44.3	45.2	48.7
TiO ₂	0.89	0.66	1.08	0.59	0.90	0.68
Al ₂ O ₃	11.5	9.5	14.5	8.4	12.3	14.7
Cr ₂ O ₃	0.19	0.29	0.09	0.33	0.14	0.11
Fe ₂ O ₃	2.2	2.3	3.8	2.5	3.8	3.2
FeO	8.5	8.1	6.9	8.3	6.3	6.8
MnO	0.18	0.18	0.18	0.18	0.16	0.19
MgO	16.8	23.1	10.8	26.7	13.1	9.3
NiO	0.07	0.17	0.03	0.20	0.05	0.04
CaO	10.2	8.6	11.7	7.6	9.0	13.7
Na ₂ O	1.20	0.96	1.41	0.93	1.64	1.58
K ₂ O	0.05	0.03	0.09	0.02	0.13	0.06
P ₂ O ₅	0.08	0.07	0.09	0.06	0.08	0.08
H ₂ O+	2.20	1.06	1.63	0.58	7.60	0.89
TOTAL	100.1	99.3	99.6	100.7	100.4	100.0
Ba	56	12	33	37	40	36
Cu	108	94	124	81	137	156
Ga	14	12	19	10	13	14
Rb	1	1	1	1	2	1
Sr	275	86	155	76	93	73
Y	19	15	22	13	20	22
Zn	60	56	54	53	65	61
Zr	52	46	75	45	70	45
Qs	-	-	-	-	-	-
Or	0.30	0.18	0.54	0.12	0.83	0.36
Ab	10.38	8.27	12.18	7.87	14.96	13.51
An	26.27	21.95	33.52	18.56	27.68	33.07
Di	19.92	16.55	20.02	14.68	15.93	28.13
Hf	15.89	9.20	24.54	7.03	24.77	17.76
Ol	21.76	38.59	1.07	46.35	7.59	0.85
Mt	3.27	3.38	5.67	3.64	5.97	4.67
Ch	0.29	0.43	0.14	0.49	0.22	0.16
Il	1.73	1.28	2.09	1.12	1.84	1.30
Ap	0.19	0.17	0.22	0.14	0.20	0.19

	<u>FF-41</u>	<u>Gb-15</u>	<u>Gd-2</u>	<u>Gd-34</u>	<u>I-64</u>	<u>I-102</u>
SiO ₂	47.1	47.0	44.1	49.2	44.2	45.8
TiO ₂	0.91	1.01	0.58	1.27	0.84	0.78
Al ₂ O ₃	13.8	14.0	8.1	14.5	10.9	11.4
Cr ₂ O ₃	0.15	0.11	0.34	0.07	0.27	0.27
Fe ₂ O ₃	2.1	3.8	1.5	2.7	2.7	1.9
FeO	7.9	6.8	9.1	6.2	7.4	8.3
MnO	0.18	0.19	0.18	0.16	0.18	0.18
MgO	13.0	12.1	26.6	8.6	19.3	18.8
NiO	0.05	0.04	0.20	0.02	0.12	0.11
CaO	12.0	11.9	7.4	14.4	9.8	10.2
Na ₂ O	1.65	1.64	0.86	1.85	0.99	1.26
K ₂ O	0.07	0.08	0.02	0.09	0.12	0.04
P ₂ O ₅	0.12	0.13	0.07	0.13	0.10	0.09
H ₂ O+	0.77	0.89	0.63	0.92	2.68	0.60
TOTAL	99.8	99.7	99.7	100.1	99.6	99.7
Ba	55	50	33	53	57	38
Cu	116	136	89	192	122	119
Ga	18	17	12	21	13	16
Rb	1	1	1	1	4	1
Sr	137	140	76	141	92	101
Y	19	24	15	28	18	18
Zn	65	65	56	47	61	52
Zr	65	62	42	77	61	61
Qz	-	-	-	0.01	-	-
Or	0.42	0.48	0.12	0.54	0.73	0.24
Ab	14.10	14.06	7.35	15.78	8.65	10.77
Ar	30.33	31.07	18.23	31.25	25.62	25.59
Di	23.42	22.13	14.70	32.04	18.99	19.77
Hy	9.28	15.09	7.23	13.56	11.02	8.85
Ol	17.13	9.25	48.32	-	28.62	29.92
Mt	3.06	5.50	2.26	3.98	4.04	2.74
Ch	0.22	0.16	0.51	0.10	0.41	0.40
Il	1.74	1.94	1.11	2.43	1.67	1.50
Ap	0.29	0.31	0.17	0.31	0.24	0.22

	<u>P-5</u>	<u>PP-10</u>	<u>PP-18</u>	<u>R-13</u>	<u>R-16</u>	<u>RBB</u>	<u>ROB</u>
SiO ₂	45.1	48.1	44.3	44.5	49.5	45.7	46.5
TiO ₂	0.61	0.96	0.60	0.80	1.32	0.95	0.97
Al ₂ O ₃	9.4	14.5	8.4	9.3	14.4	13.5	13.6
Cr ₂ O ₃	0.28	0.10	0.35	0.33	0.05	0.12	0.14
Fe ₂ O ₃	2.5	1.3	1.6	3.4	2.7	5.3	5.4
FeO	8.5	8.6	9.2	7.5	6.3	4.8	4.6
MnO	0.18	0.18	0.18	0.18	0.17	0.16	0.16
MgO	21.1	10.8	25.3	22.7	8.0	13.0	11.2
NiO	0.12	0.03	0.19	0.18	0.02	0.04	0.05
CaO	7.6	12.2	7.4	8.5	14.5	8.0	8.1
Na ₂ O	0.84	1.74	1.07	1.08	1.91	0.89	0.83
K ₂ O	0.12	0.15	0.13	0.05	0.09	0.15	0.30
P ₂ O ₅	0.06	0.11	0.09	0.10	0.13	0.12	0.07
H ₂ O+	3.25	0.82	0.58	0.79	0.52	7.64	8.40
TOTAL	99.7	99.6	99.4	99.4	99.6	100.4	100.3
Ba	78	35	68	12	46	60	56
Cu	83	142	55	105	108	161	207
Ga	11	16	11	10	22	14	10
Rb	1	3	3	1	1	3	5
Sr	458	154	94	102	177	314	376
Y	14	23	12	14	28	21	21
Zn	60	66	65	67	36	66	66
Zr	28	69	56	50	76	67	67
Qz	-	-	-	-	0.73	3.95	7.55
Or	0.73	0.90	0.78	0.30	0.54	0.96	1.93
Ab	7.36	14.93	9.17	9.26	16.32	8.12	7.64
An	22.24	31.75	17.96	20.68	30.70	34.94	35.36
Di	13.23	23.19	14.74	16.90	33.01	5.64	6.27
Hy	24.12	13.36	6.10	11.23	11.83	35.64	30.34
Ol	26.71	11.70	46.98	34.30	-	-	-
Mt	3.82	1.91	2.38	5.05	3.95	8.30	8.50
Ch	0.43	0.15	0.52	0.49	0.07	0.19	0.22
Il	1.20	1.85	1.15	1.54	2.53	1.95	2.00
Ap	0.15	0.26	0.22	0.24	0.31	0.31	0.18

	<u>ROB</u>	<u>S-28</u>	<u>SOG</u>	<u>T-42</u>	<u>T-47</u>	<u>T-55</u>
SiO ₂	44.0	45.0	46.8	46.2	47.0	47.7
TiO ₂	0.57	0.71	0.86	0.99	1.08	1.02
Al ₂ O ₃	8.0	10.0	13.3	12.4	13.7	13.6
Cr ₂ O ₃	0.38	0.30	0.15	0.18	0.14	0.14
Fe ₂ O ₃	2.1	2.1	3.3	2.9	2.1	5.1
FeO	8.9	8.5	6.4	7.8	7.9	5.7
MnO	0.18	0.17	0.16	0.17	0.16	0.18
MgO	26.5	21.5	13.3	14.8	12.5	12.6
NiO	0.19	0.15	0.05	0.07	0.05	0.05
CaO	6.8	9.4	10.7	11.4	12.3	11.5
Na ₂ O	0.95	1.11	1.42	1.52	1.67	1.70
K ₂ O	0.11	0.03	0.11	0.06	0.06	0.14
P ₂ O ₅	0.09	0.09	0.10	0.12	0.12	0.11
H ₂ O+	0.63	0.64	3.60	1.04	1.06	1.00
TOTAL	99.4	99.7	100.3	99.7	99.8	100.5
Ba	69	37	45	56	50	90
Cu	62	112	119	135	139	91
Ga	9	13	16	16	17	19
Rb	2	1	2	1	2	1
Sr	79	92	121	148	160	152
Y	12	15	21	18	22	24
Zn	61	55	66	65	65	52
Zr	51	50	63	75	75	80
Qz	-	-	-	-	-	-
Or	0.66	0.18	0.67	0.36	0.36	0.83
Ab	8.15	9.48	12.44	13.07	14.30	14.46
An	17.47	22.49	30.49	27.21	29.98	29.11
Di	12.61	19.03	19.05	23.36	24.95	21.91
Hy	9.19	7.36	22.41	9.90	8.77	18.73
Ol	47.02	36.36	7.76	19.41	15.94	5.13
Mt	3.03	3.07	5.01	4.23	3.14	7.40
Ch	0.57	0.45	0.23	0.27	0.21	0.21
Il	1.10	1.36	1.69	1.91	2.08	1.95
Ap	0.22	0.22	0.25	0.29	0.29	0.26

	<u>512</u>	<u>513⁺</u>	<u>513⁻</u>	<u>520</u>	<u>529</u>	<u>534</u>	<u>539</u>
SiO ₂	42.1	44.5	44.5	48.4	43.1	48.3	46.5
TiO ₂	0.62	1.24	1.56	1.89	0.97	1.53	1.29
Al ₂ O ₃	6.9	13.3	10.7	14.1	7.9	13.4	11.4
Cr ₂ O ₃	0.28	0.12	0.14	0.03	0.17	0.09	0.19
Fe ₂ O ₃	1.8	3.4	4.0	3.9	3.0	2.9	2.9
FeO	9.5	6.2	7.6	8.1	9.9	7.9	8.4
MnO	0.17	0.15	0.18	0.20	0.20	0.17	0.17
MgO	27.7	9.6	11.6	6.3	23.5	11.1	15.6
NiO	0.20	0.04	0.05	0.01	0.13	0.05	0.09
CaO	6.7	12.2	13.0	12.6	7.6	11.5	10.9
Na ₂ O	0.85	1.24	1.09	2.41	0.88	2.14	1.62
K ₂ O	0.17	0.16	0.13	0.22	0.31	0.16	0.11
P ₂ O ₅	0.08	0.15	0.16	0.20	0.15	0.17	0.14
H ₂ O ⁺	3.05	7.39	5.58	1.15	2.71	0.96	0.85
TOTAL	100.1	99.7	100.3	99.5	100.5	100.4	100.2
Ba	101	77	42	48	67	84	41
Cu	56	137	132	224	96	201	127
Ga	11	21	20	22	14	21	17
Rb	4	3	4	5	6	2	2
Sr	204	416	275	209	132	210	192
Y	8	19	24	29	17	26	20
Zn	61	57	66	87	68	65	67
Zr	46	76	85	126	66	100	84
Qz	-	-	-	1.03	-	-	-
Or	1.04	1.02	0.81	1.32	1.88	0.95	0.66
Ab	7.41	11.37	9.75	20.76	7.62	18.23	13.81
An	14.87	32.78	25.13	27.49	16.98	26.53	23.55
Di	15.10	25.47	33.53	28.12	16.22	23.95	23.90
Hy	0.41	20.36	14.62	11.40	8.62	13.29	9.83
Ol	56.61	0.51	6.28	-	41.70	9.29	20.93
Mt	2.72	5.36	6.14	5.70	4.47	4.28	4.24
Ch	0.42	0.19	0.22	0.04	0.26	0.13	0.28
Il	1.21	2.55	3.13	3.65	1.89	2.93	2.47
Ap	0.20	0.38	0.40	0.48	0.36	0.41	0.33

	<u>544</u>	<u>546</u>	<u>548</u>	<u>554</u>	<u>578</u>	<u>580</u>	<u>583</u>
SiO ₂	45.4	41.6	45.8	49.0	49.8	49.4	47.9
TiO ₂	1.09	0.70	1.29	2.02	2.03	2.55	2.93
Al ₂ O ₃	11.2	5.5	11.5	13.8	13.9	13.1	14.4
Cr ₂ O ₃	0.23	0.25	0.19	0.03	0.03	0.01	0.02
Fe ₂ O ₃	3.4	3.2	2.9	2.6	4.1	4.2	4.5
FeO	7.8	8.0	8.2	9.6	8.8	10.0	7.8
MnO	0.17	0.17	0.17	0.20	0.21	0.21	0.17
MgO	17.8	30.6	15.7	6.1	6.0	5.3	5.3
NiO	0.12	0.27	0.09	0.01	0.01	0.01	0.01
CaO	10.5	5.1	10.6	12.0	12.0	11.1	11.5
Na ₂ O	1.48	0.60	1.65	2.51	2.60	2.61	2.77
K ₂ O	0.08	0.18	0.12	0.15	0.20	0.40	0.85
P ₂ O ₅	0.14	0.09	0.18	0.22	0.23	0.30	0.37
H ₂ O ⁺	1.08	3.24	1.05	0.97	0.50	0.91	1.01
TOTAL	100.5	99.5	99.4	99.2	100.4	100.1	99.5
Ba	27	69	48	83	88	181	284
Cu	198	76	130	235	214	245	169
Ga	18	9	19	23	25	22	23
Rb	1	4	3	3	2	4	15
Sr	141	163	177	221	224	256	408
Y	20	12	20	30	35	39	35
Zn	78	68	75	83	81	87	83
Zr	73	48	89	132	136	179	208
Qz	-	-	-	0.91	2.51	3.47	0.72
Or	0.48	1.11	0.72	0.90	1.18	2.39	5.10
Ab	12.60	5.28	14.19	21.62	22.04	22.29	23.79
An	23.79	12.31	24.02	26.47	25.63	22.92	24.74
Di	21.97	10.49	22.52	26.91	26.52	25.02	24.94
Hy	6.30	9.79	8.29	14.92	11.70	12.14	7.54
Ol	27.15	54.17	22.86	-	-	-	-
Mt	4.97	4.87	4.20	3.79	5.97	6.16	6.59
Ch	0.34	0.38	0.28	0.04	0.04	0.01	0.03
Il	2.08	1.38	2.49	3.91	3.86	4.89	5.65
Ap	0.33	0.22	0.43	0.53	0.55	0.72	0.89

	<u>586</u>	<u>589</u>	<u>592</u>	<u>593</u>	<u>594</u>	<u>598</u>
SiO ₂	48.8	48.3	44.4	42.1	48.0	44.2
TiO ₂	1.46	3.12	1.19	0.93	2.23	1.51
Al ₂ O ₃	15.1	13.6	10.6	6.4	13.8	12.3
Cr ₂ O ₃	0.05	0.02	0.20	0.29	0.03	0.09
Fe ₂ O ₃	5.9	7.5	3.1	2.8	5.4	3.0
FeO	4.9	7.1	7.9	8.3	7.0	7.7
MnO	0.16	0.20	0.17	0.17	0.19	0.17
MgO	6.6	5.3	17.9	27.8	6.2	11.1
NiO	0.01	0.01	0.12	0.23	0.01	0.04
CaO	12.9	10.7	9.8	6.2	12.5	13.0
Na ₂ O	2.21	2.64	1.41	0.98	2.49	1.53
K ₂ O	0.11	0.32	0.16	0.15	0.26	0.81
P ₂ O ₅	0.16	0.35	0.12	0.13	0.24	0.29
H ₂ O+	1.49	0.77	2.19	3.63	1.03	3.65
TOTAL	<u>99.9</u>	<u>99.9</u>	<u>99.3</u>	<u>100.1</u>	<u>99.4</u>	<u>99.4</u>
Ba	49	101	52	69	81	158
Cu	159	331	105	47	162	135
Ga	19	22	16	9	23	19
Rb	1	3	3	4	2	17
Sr	217	215	271	271	338	464
Y	25	49	21	12	30	24
Zn	66	99	72	72	84	65
Zr	101	232	75	67	137	113
Qz	4.70	6.77	-	-	2.34	-
Or	0.66	1.91	0.97	0.92	1.56	5.00
Ab	19.04	22.55	12.30	8.60	21.44	11.14
An	31.58	24.57	22.67	13.09	26.24	25.40
Ne	-	-	-	-	-	1.30
Di	25.43	21.14	21.16	14.24	28.10	32.02
Hy	6.67	5.30	7.31	4.69	7.49	-
Ol	-	-	28.05	51.70	-	16.72
Mt	8.64	10.90	4.60	4.17	7.89	4.56
Ch	0.07	0.03	0.30	0.44	0.04	0.14
Il	2.82	5.98	2.33	1.83	4.31	3.00
Ap	0.39	0.84	0.29	0.32	0.58	0.72

	<u>599⁺</u>	<u>599⁻</u>	<u>600</u>	<u>625*</u>	<u>629</u>	<u>630**</u>
SiO ₂	47.2	46.8	48.2	64.9	46.6	63.8
TiO ₂	1.55	1.56	1.72	0.88	3.00	0.81
Al ₂ O ₃	13.4	13.4	13.6	17.4	13.6	15.8
Cr ₂ O ₃	0.10	0.10	0.07	0.00	0.02	0.00
Fe ₂ O ₃	2.3	2.6	2.1	1.6	3.0	4.4
FeO	8.4	8.5	9.1	0.3	10.1	0.7
MnO	0.17	0.17	0.18	0.10	0.20	0.13
MgO	10.2	10.2	9.8	0.2	4.8	0.7
NiO	0.04	0.04	0.04	0.00	0.01	0.00
CaO	11.6	11.7	12.2	1.0	11.8	1.5
Na ₂ O	1.98	1.97	2.17	5.72	2.58	6.15
K ₂ O	0.20	0.19	0.20	5.64	0.83	4.75
P ₂ O ₅	0.17	0.17	0.17	0.27	0.40	0.24
CO ₂	-	-	-	-	2.09	-
H ₂ O ⁺	2.90	2.77	0.64	1.75	0.77	0.57
TOTAL	100.2	100.2	100.2	99.8	99.8	99.6
Ba	130	96	60	nd	275	1150
Cu	120	142	197	nd	175	0
Ga	19	20	22	34	23	33
Rb	2	2	3	72	19	62
Sr	241	236	239	164	396	108
Y	24	22	26	nd	39	49
Zn	72	73	72	nd	86	78
Zr	97	84	110	nd	225	324
Qz	-	-	-	8.94	1.75	7.27
Or	1.22	1.16	1.19	34.02	4.95	28.39
Ab	17.24	17.15	18.47	49.41	22.04	52.63
An	27.98	27.81	26.80	1.50	23.16	1.61
Di	24.07	24.79	26.71	-	16.53	3.26
Hy	13.41	11.57	9.31	0.51	15.57	0.23
Ol	9.07	10.06	10.61	-	-	-
Mt	3.43	3.85	3.11	-	4.45	0.21
Ch	0.15	0.15	0.10	-	0.03	-
Il	3.03	3.05	3.29	0.80	5.75	1.56
Ap	0.41	0.41	0.41	0.65	0.96	0.57
Ct	-	-	-	-	4.80	-

* with 1.34 Cor, 1.65 Hem and 1.17 Titanite

** with 4.29 Hem

	<u>635</u>	<u>636</u>	<u>638</u>	<u>640</u>	<u>641</u>	<u>642</u>
SiO ₂	47.8	48.2	46.2	42.7	44.0	43.8
TiO ₂	2.24	2.12	2.90	0.91	1.31	1.29
Al ₂ O ₃	13.9	14.4	15.4	5.8	9.5	9.1
Cr ₂ O ₃	0.02	0.03	0.02	0.24	0.24	0.22
Fe ₂ O ₃	3.7	3.8	3.7	2.6	3.3	3.0
FeO	9.2	8.2	7.5	9.1	7.3	8.5
MnO	0.20	0.19	0.16	0.17	0.17	0.17
MgO	5.3	5.9	4.4	28.9	20.7	21.0
NiO	0.01	0.01	0.01	0.24	0.15	0.16
CaO	11.4	12.1	11.3	5.8	8.7	8.1
Na ₂ O	2.42	2.45	2.87	1.00	1.78	1.71
K ₂ O	0.21	0.18	0.38	0.20	0.19	0.08
P ₂ O ₅	0.23	0.21	0.33	0.10	0.14	0.15
CO ₂	2.60	1.64	3.28	-	-	-
H ₂ O+	0.88	0.74	1.14	1.89	2.03	2.48
TOTAL	100.1	100.2	99.6	99.7	99.5	99.8
Ba	70	66	136	81	69	49
Cu	254	205	269	69	74	101
Ga	23	24	27	10	15	19
Rb	4	2	4	3	3	3
Sr	229	236	304	142	265	142
Y	30	38	38	15	17	16
Zn	79	72	84	70	67	73
Zr	146	137	197	68	96	84
Qz	6.18	4.14	5.61	-	-	-
Or	1.25	1.07	2.28	1.21	1.15	0.49
Ab	20.64	20.85	24.67	8.66	15.10	14.88
An	16.57	27.79	28.46	11.00	17.84	17.40
Ne	-	-	-	-	0.20	-
Di	10.23	17.00	4.18	14.17	20.34	18.30
Hy	18.96	15.22	15.34	3.99	-	2.52
Ol	-	-	-	54.77	37.22	38.75
Mt	5.33	5.59	5.46	3.83	4.90	4.44
Ch	0.03	0.04	0.03	0.36	0.36	0.33
Il	4.29	4.05	5.60	1.77	2.55	2.52
Ap	0.55	0.50	0.79	0.24	0.34	0.37
Ct	5.96	3.75	7.58	-	-	-

	<u>643</u>	<u>648</u>	<u>649</u>	<u>651</u>	<u>655</u>	<u>658</u>
SiO ₂	43.1	44.5	42.9	43.9	44.8	43.9
TiO ₂	1.09	1.12	0.89	1.11	1.23	1.30
Al ₂ O ₃	7.3	10.1	7.4	9.8	10.5	9.6
Cr ₂ O ₃	0.23	0.23	0.27	0.23	0.22	0.21
Fe ₂ O ₃	2.6	3.8	2.2	3.6	4.0	4.1
FeO	8.7	7.8	9.2	7.7	7.5	7.3
MnO	0.17	0.18	0.17	0.17	0.18	0.17
MgO	25.3	19.4	25.4	19.4	18.4	18.2
NiO	0.20	0.15	0.20	0.15	0.12	0.12
CaO	6.9	10.1	7.2	10.0	9.7	8.9
Na ₂ O	0.98	1.31	0.91	1.20	1.47	1.20
K ₂ O	0.46	0.09	0.11	0.06	0.12	0.11
P ₂ O ₅	0.12	0.11	0.12	0.12	0.14	0.17
H ₂ O ⁺	2.30	1.51	2.54	2.39	1.76	4.78
TOTAL	<u>99.5</u>	<u>100.4</u>	<u>99.5</u>	<u>99.8</u>	<u>100.1</u>	<u>100.1</u>
Ba	86	62	32	36	66	58
Cu	91	127	84	131	110	122
Ga	9	17	11	15	15	19
Rb	7	1	1	2	1	2
Sr	137	183	265	170	217	206
Y	20	17	13	14	18	16
Zn	66	71	73	67	67	85
Zr	79	78	53	78	78	87
Qz	-	-	-	-	-	-
Or	2.80	0.54	0.67	0.36	0.72	0.68
Ab	8.53	11.22	7.94	10.42	12.65	10.67
An	14.66	21.72	16.27	21.74	21.92	21.60
Di	15.68	22.26	15.57	22.56	20.55	18.62
Hy	5.61	5.86	7.46	6.62	8.77	18.12
Ol	46.08	30.03	46.33	30.09	26.42	20.75
Mt	3.88	5.62	3.32	5.40	5.93	6.21
Ch	0.35	0.34	0.41	0.35	0.33	0.32
Il	2.13	2.15	1.74	2.16	2.37	2.59
Ap	0.29	0.26	0.29	0.29	0.34	0.42

	<u>661</u>	<u>662</u>	<u>664</u>	<u>669</u>	<u>670</u>	<u>671</u>
SiO ₂	51.5	47.7	48.4	44.2	48.0	46.6
TiO ₂	1.47	2.16	1.55	1.25	2.02	1.43
Al ₂ O ₃	15.2	14.4	13.2	9.6	14.0	12.5
Cr ₂ O ₃	0.06	0.04	0.07	0.22	0.06	0.14
Fe ₂ O ₃	3.5	4.0	4.8	4.9	2.2	2.8
FeO	6.2	7.8	6.1	6.5	9.4	8.3
MnO	0.15	0.18	0.17	0.17	0.18	0.17
MgO	6.5	6.8	8.5	19.0	7.6	13.2
NiO	0.01	0.02	0.02	0.14	0.02	0.07
CaO	10.5	12.2	9.9	8.9	12.3	11.3
Na ₂ O	2.75	2.38	3.42	1.54	2.38	1.82
K ₂ O	0.74	0.53	0.39	0.32	0.16	0.17
P ₂ O ₅	0.18	0.24	0.17	0.16	0.21	0.15
H ₂ O ⁺	<u>1.64</u>	<u>1.38</u>	<u>3.11</u>	<u>2.57</u>	<u>0.78</u>	<u>1.14</u>
TOTAL	100.4	99.8	99.8	99.5	99.3	99.8
Ba	368	142	177	44	77	93
Cu	73	187	115	110	185	143
Ga	22	24	17	17	24	17
Rb	9	8	7	4	6	2
Sr	277	342	405	204	292	221
Y	22	29	27	15	30	23
Zn	72	70	72	76	61	65
Zr	145	146	92	76	129	90
Qz	3.37	-	-	-	-	-
Or	4.43	3.18	2.39	1.95	0.96	1.02
Ab	23.57	20.47	29.98	13.45	20.44	15.61
An	27.40	27.34	20.22	18.96	27.53	25.84
Di	19.28	26.27	23.31	20.14	26.95	23.96
Hy	13.54	11.07	7.02	8.90	10.60	9.10
Ol	-	0.93	6.32	26.09	5.79	16.99
Mt	5.07	5.92	7.19	7.32	3.24	4.16
Ch	0.09	0.06	0.11	0.33	0.09	0.21
Il	2.83	4.17	3.05	2.45	3.89	2.75
Ap	0.43	0.58	0.42	0.39	0.50	0.36

chilled margins, as well as to avoid the possible zeolite-bearing vesicles of the upper parts of the flows. Evidence suggests that the zeolites are of magmatic origin, including

- 1) occurrence of zeolites at the centres of rapidly chilled blocks in the breccias
- 2) the presence of zeolites in cavities in the sideromelane where diffusion rates of, and/or permeability by, aqueous solutions are presumed to be low
- 3) restriction of zeolites to certain flows in the volcanic sequence; noteworthy are the zeolite-bearing "grey flows" found amongst the predominantly feldspar-phyric basalts which have vesicle infillings of agate

However, rather than prejudice the entire batch of analyses towards any specific concept of zeolite origin, samples were analyzed as they came from the field except for the removal of weathered surfaces. Sample 599 with approximately 2% of amygdaloidal zeolites was analyzed both with its zeolites (599⁺) and without (599⁻). Similarly, sample 513, representing the leucocratic differentiate of a thick flow (the base of which is represented by 512), was analyzed both with (513⁺) and without (513⁻) its zeolites. Both of these latter compositions are plotted on most of the variation diagrams, and usually the tie line 512-513⁺ more nearly matches the over-all trend in the province than would the one for 512-513⁻, suggesting that the province evolved with potential magmatic zeolites, rather than having had them formed as a separate event at some later date. Either that or they may be the products of a later mild deuteric event which did not allow communication between alteration effects in adjacent flows.

A perusal of the analyses in Table 2 may raise the question as to why so many apparently cumultic rocks were analyzed, since in any meaningful discussion

of fractionation trends liquid compositions are required. This question is fully answered in Chapter 4, the foundation of which is that liquid compositions in equilibrium with peridotite at high pressure and low pressure may have very different compositions. This is not to say that some olivine cumulates have not been analyzed, but there appear to be criteria for distinguishing between what were high-pressure picritic liquids and what may be just low-pressure, olivine-rich cumulates precipitated from a slightly undersaturated basaltic magma.

II. General Comments on the Analyses

Several notable features of the analyses are listed below:

- 1) there are high levels of MgO and correspondingly high Cr and Ni in most of the basalts
- 2) breccias are characterized by $H_2O^+ > 3.00\%$ and are often associated with slightly lower levels of MnO and sometimes erratic enrichment in Sr
- 3) the so-called "incompatible elements" (Ringwood, 1966a) (i.e. elements which are largely rejected from the structures of the major silicate phases of basalts) including, amongst others, Ti, K, P, Zr, Rb, Sr, Ba and Y are generally remarkably low, even for tholeiites (comparisons are made in a succeeding section)
- 4) samples A-5 and 6; AA-19, 26, 30 and 63 were taken from a single flow showing strong intra-flow differentiation; similarly, PP-10 and 18; R-13 and 16; 512, 513⁺ and 513⁻; in most of the variation diagrams these intra-flow differentiates are joined by tie lines
- 5) all specimens were analyzed for Pb but none was found to be above the theoretical lower limit of detection of 6 ppm.

III. Variation Diagrams

A modified Harker variation diagram with MgO as abscissa was first introduced by Powers (1955). This type of diagram (Fig. 7A, B) is very useful for the Baffin Bay basalts since (i) there is a greater range in MgO than in any other oxide; (ii) field relations suggest that fractionation of olivine has been the principal mechanism in controlling differentiation; and (iii) the correlation coefficient between MgO and the Thornton-Tuttle differentiation index (1960) is large. Therefore, MgO may be used as a simple and meaningful index of differentiation.

Several general features may be noted in Figs. 7A, B such as the slightly lower levels of SiO_2 and Al_2O_3 in Svartenhuk, whereas in the same rocks total iron and the minor elements are slightly higher. In the case of each oxide, parallel, converging or even coincident trends are developed along what may be described as fairly long control lines. Extrapolation of the CaO , TiO_2 and Na_2O trend lines to their zero points suggests that the removal of a phase with 42-46% MgO could have been responsible for the observed variation. In addition, that phase should consist of roughly 13.5% total iron as Fe_2O_3 and 39-41% SiO_2 . Compositions of olivines (Deer et al., 1962) corresponding to the Baffin Bay olivines, determined by X-ray diffractometer, have also been plotted. It may be seen that the removal of forsteritic olivine from the most picritic compositions (or addition or removal of olivine to or from some intermediate composition) could effect most of the observed variation. Also plotted on these diagrams are the intra-flow differentiates and the Svartenhuk feldspar-phyric basalts. It is clear that the evolution of the feldspar-phyric basalts cannot have been controlled simply by olivine removal, since the late-stage trends are usually widely divergent from the olivine control lines. The development of these rocks is discussed in the concluding section of

Fig. 7A, B. MgO Variation Diagram.

■ = Olivine analysis (Deer et al., 1962, Vol. 1, Table 2, Anal. 7-10).

Fig. 8. MgO-Ni Variation Diagram.

K = Kilauean basalts (Nockolds and Allen, 1956).

M = Mauna Loa basalts (Nockolds and Allen, 1956).

N = Nuanetsi basalts (Jamieson, pers. comm.).

Fig. 9. TiO_2 -Zr Variation Diagram.

Fig. 10. TiO_2 - P_2O_5 Variation Diagram.

Fig. 11. K_2O - P_2O_5 Variation Diagram.

Fig. 12. CaO-Y Variation Diagram.

Fig. 13. CaO-Sr Variation Diagram.

Fig. 14. Total Alkalies-Silica Variation Diagram.

Line of Macdonald and Katsura (1964) separates tholeiites from alkali basalts of Hawaii.

Fig. 15. A-F-M Variation Diagram.

A = $\text{Na}_2\text{O} + \text{K}_2\text{O}$ F = Total Iron as Fe_2O_3 M = MgO

Fig. 16. C-N-K Variation Diagram.

C = CaO N = Na_2O K = K_2O

Fig. 17. K-Rb Variation Diagram.

Symbols Common to Figs. 7-17

- Baffin Island normal lava or breccia.
- Baffin Island intra-flow differentiate.
- ▲ Svartenhuk normal lava or breccia.
- △ Svartenhuk intra-flow differentiate.
- ✕ Svartenhuk trachyte.

Tie lines join intra-flow differentiates.

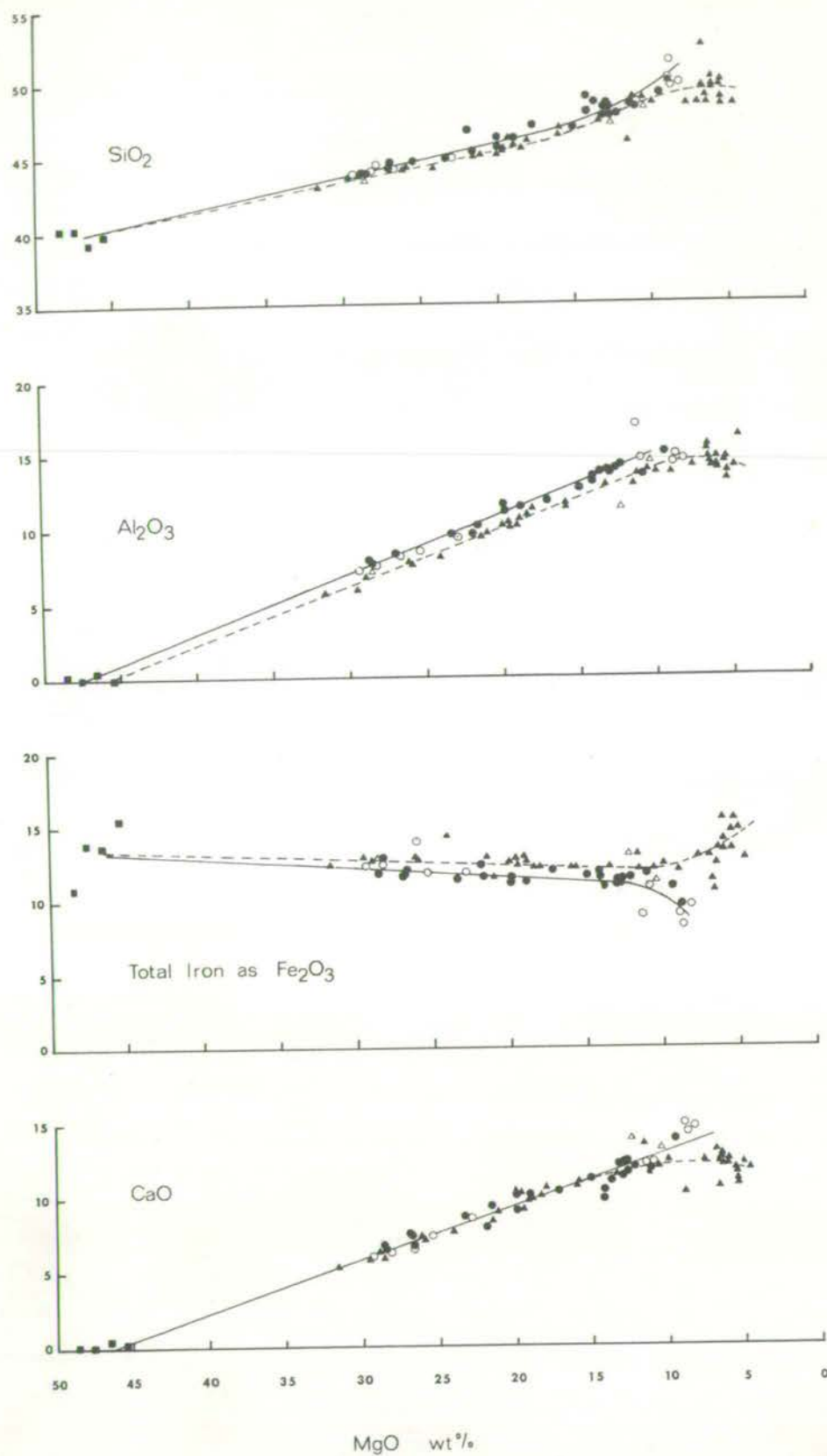


FIG. 7A

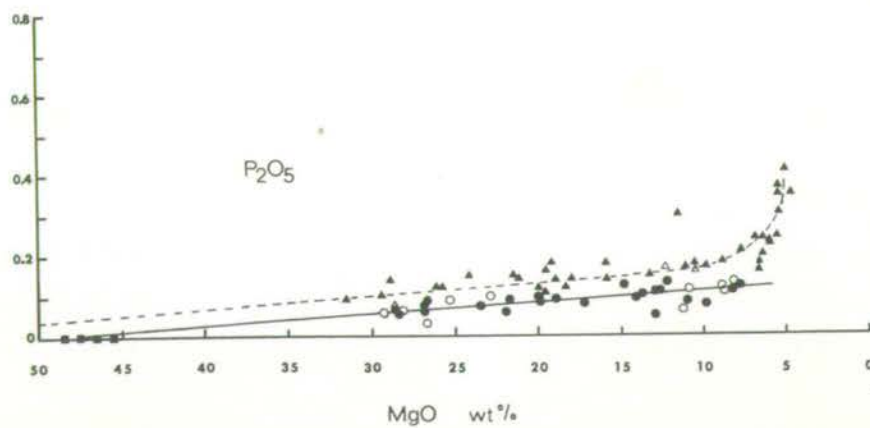
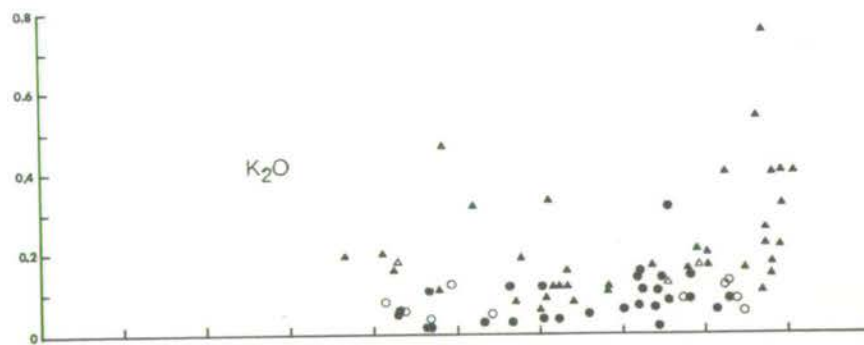
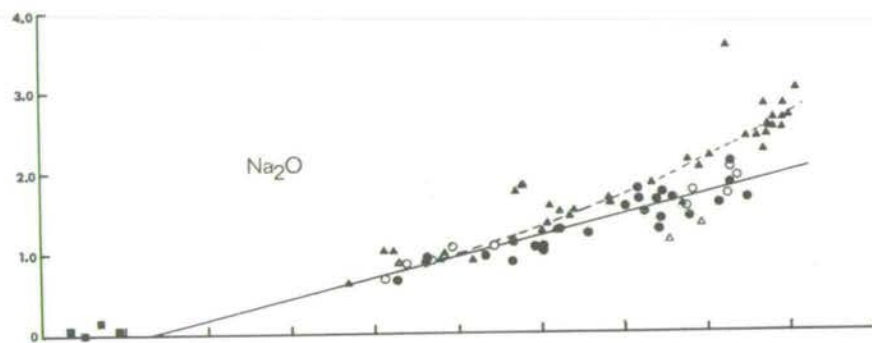
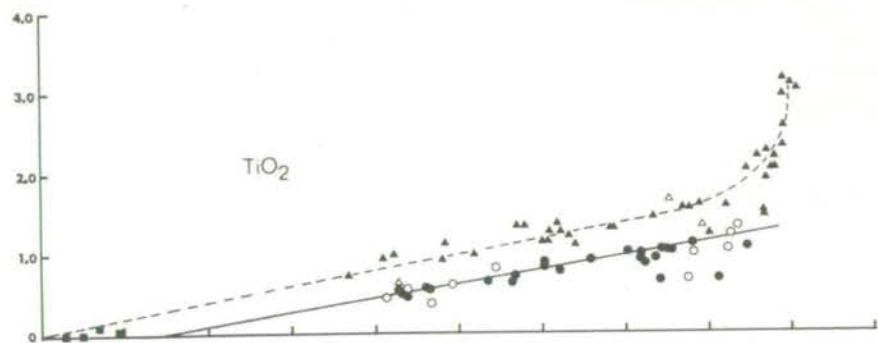
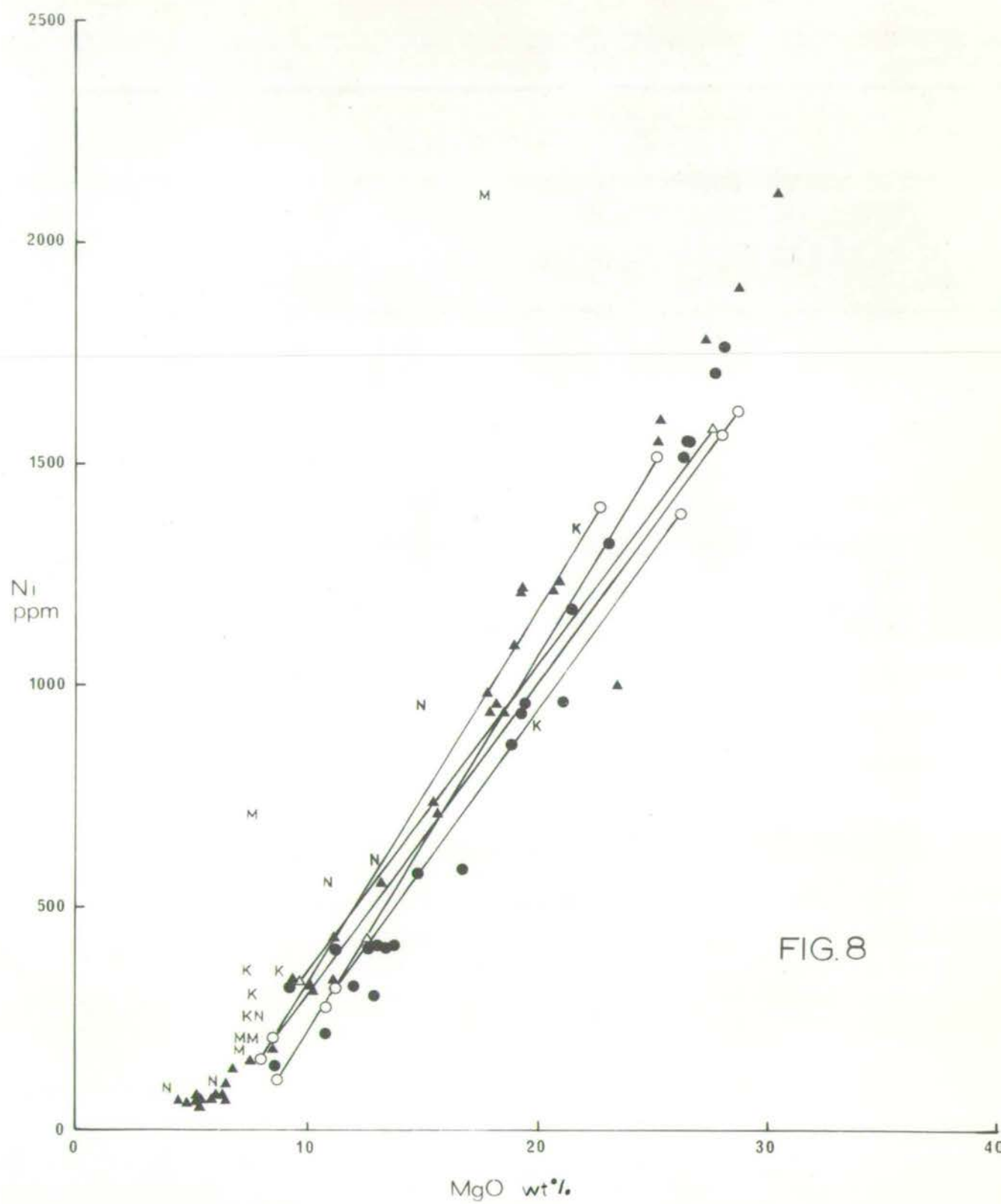


FIG. 7B



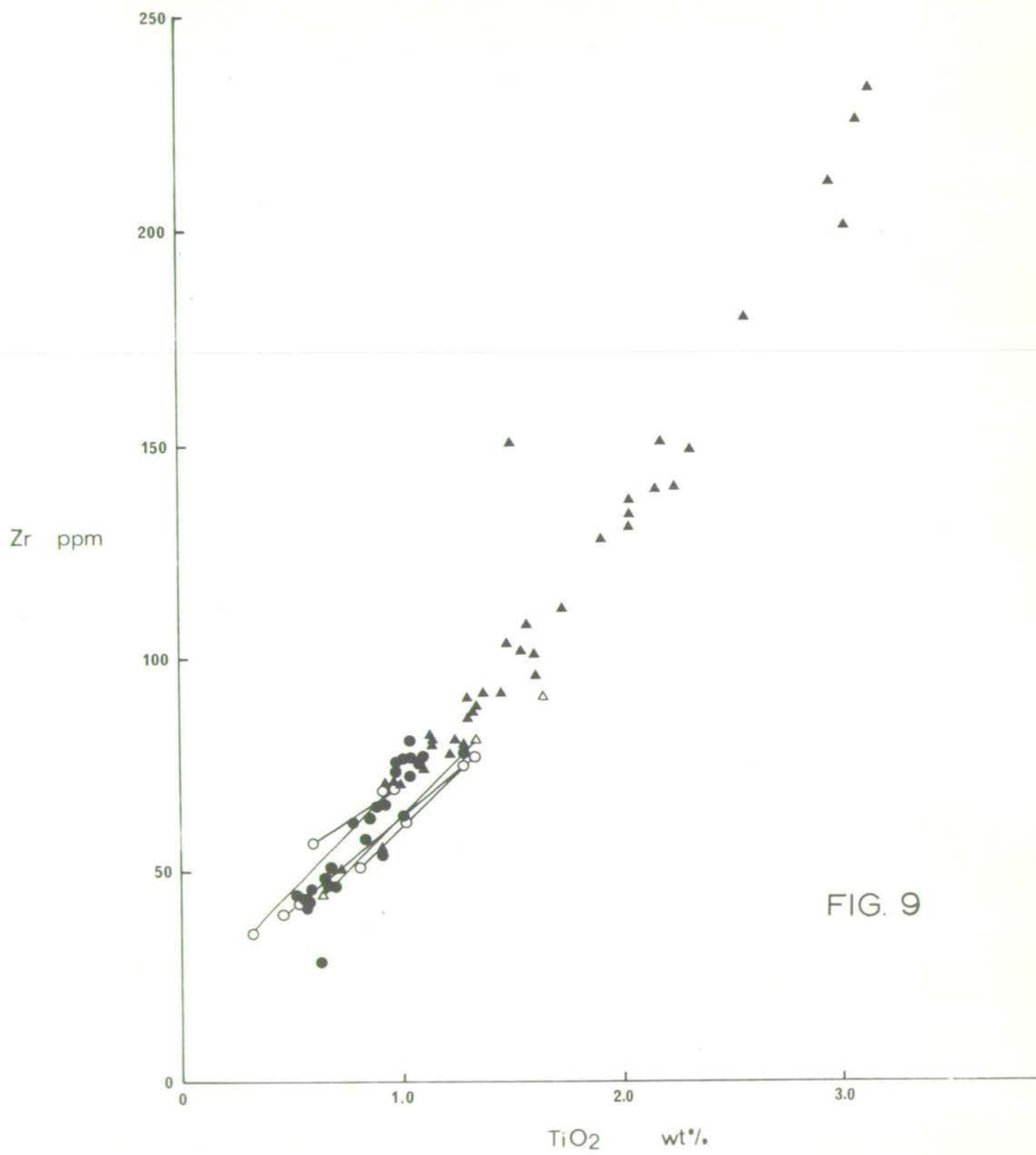
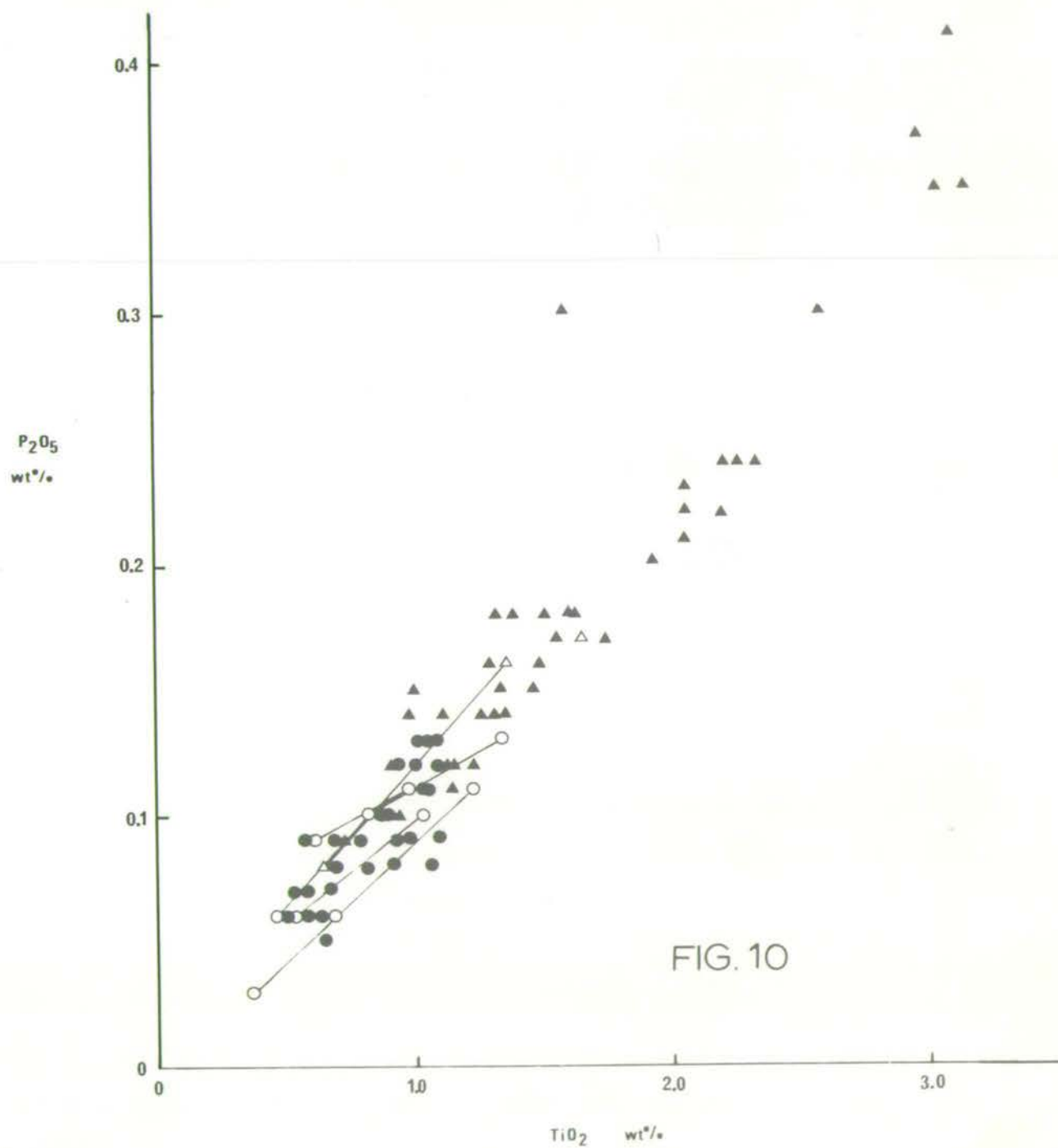
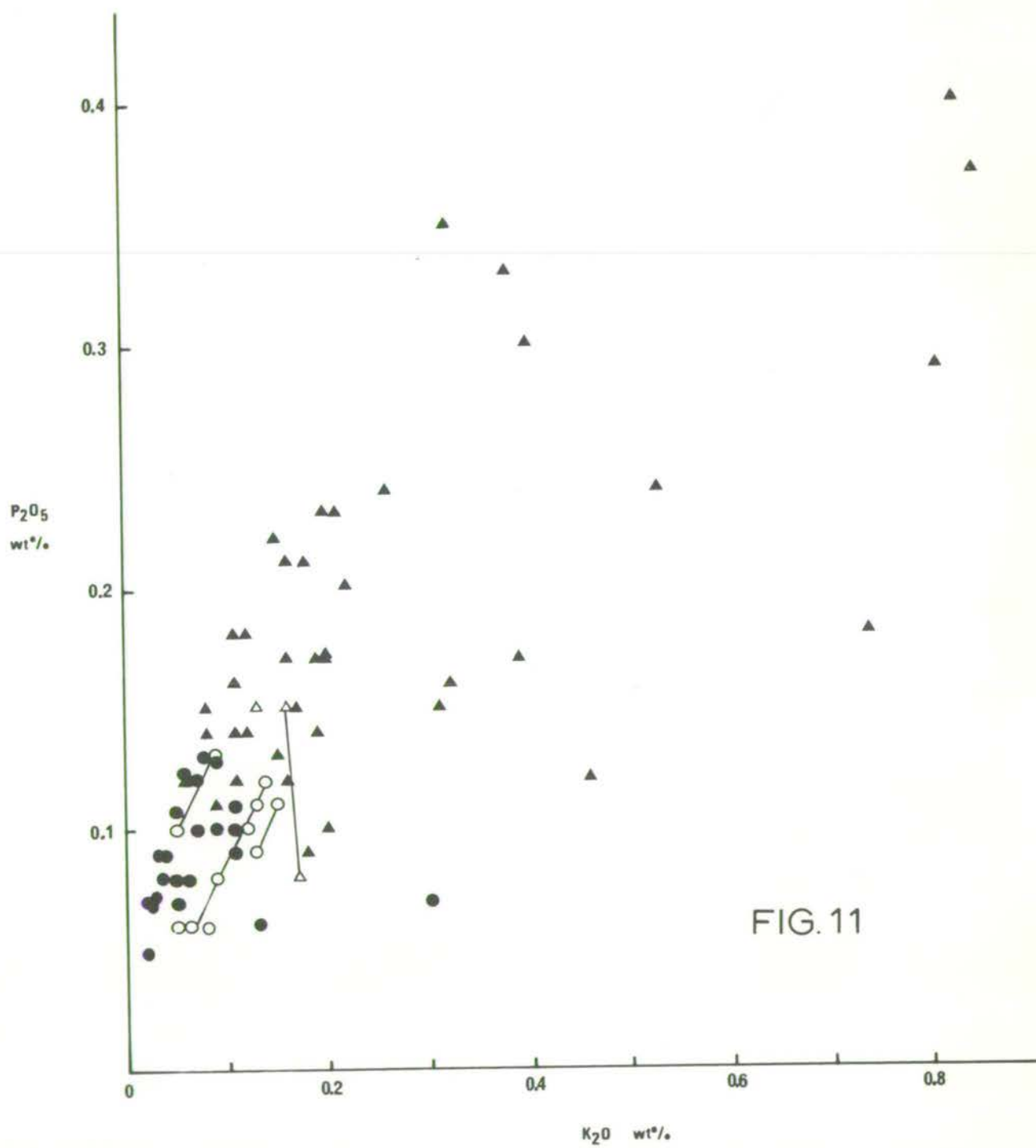


FIG. 9





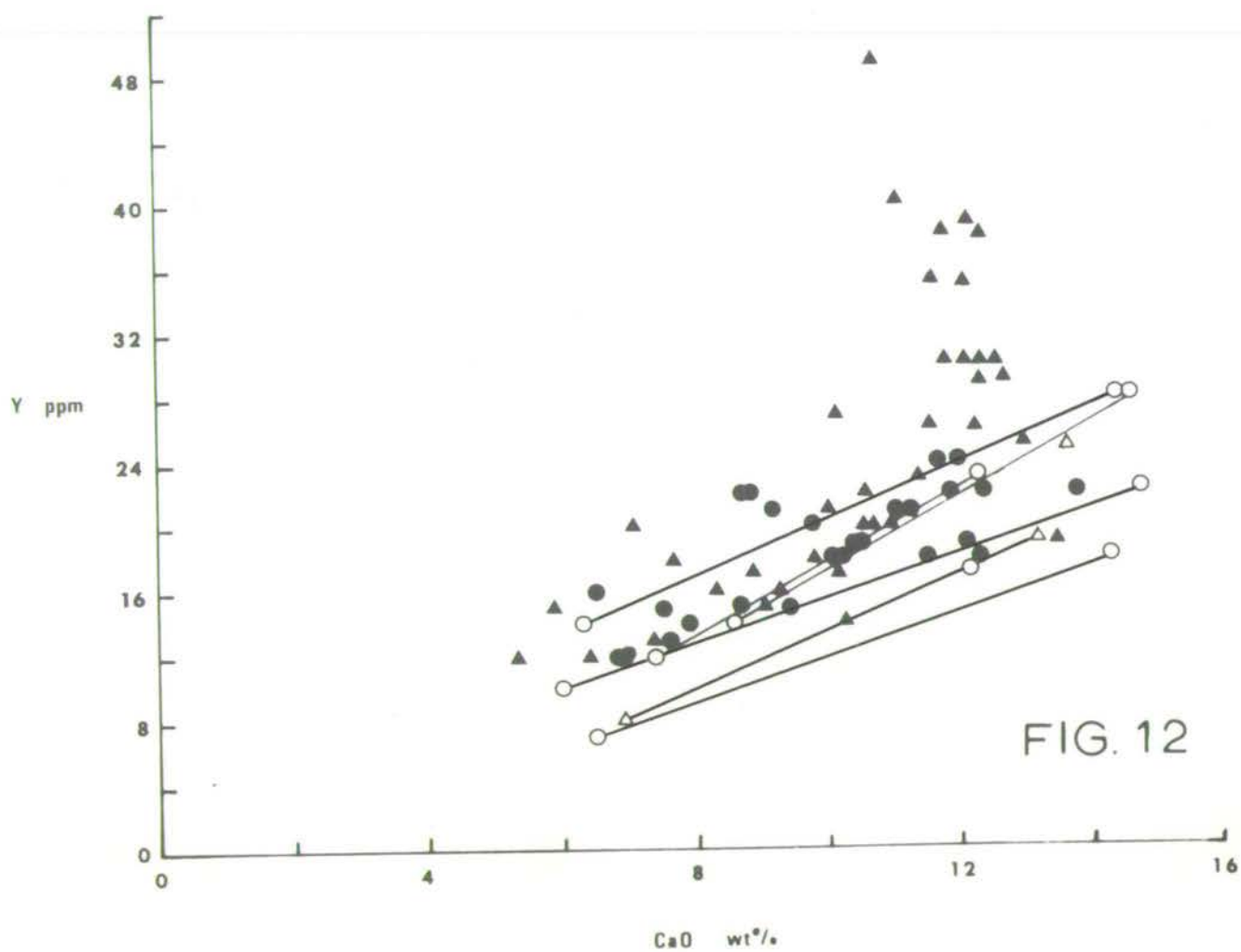
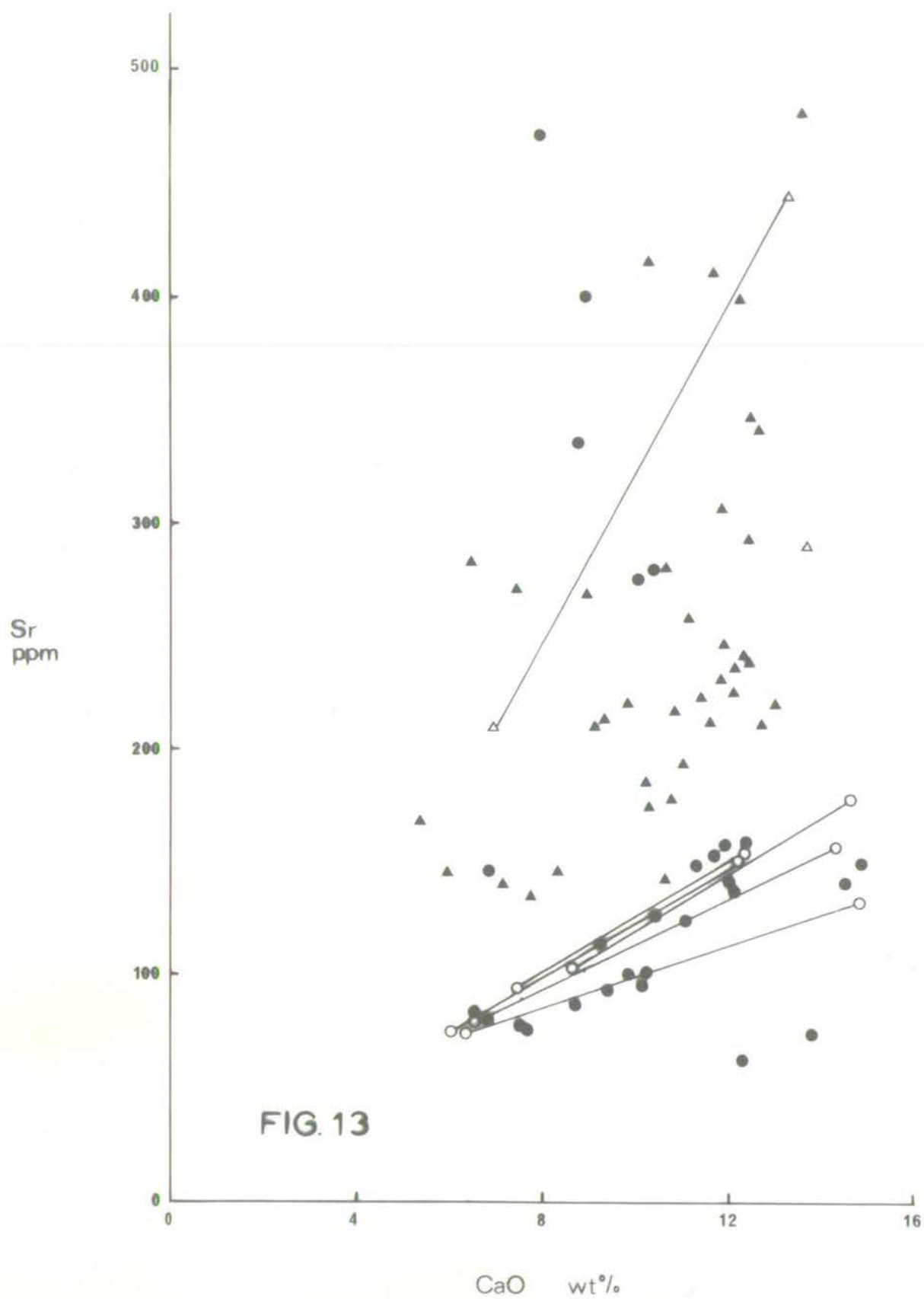
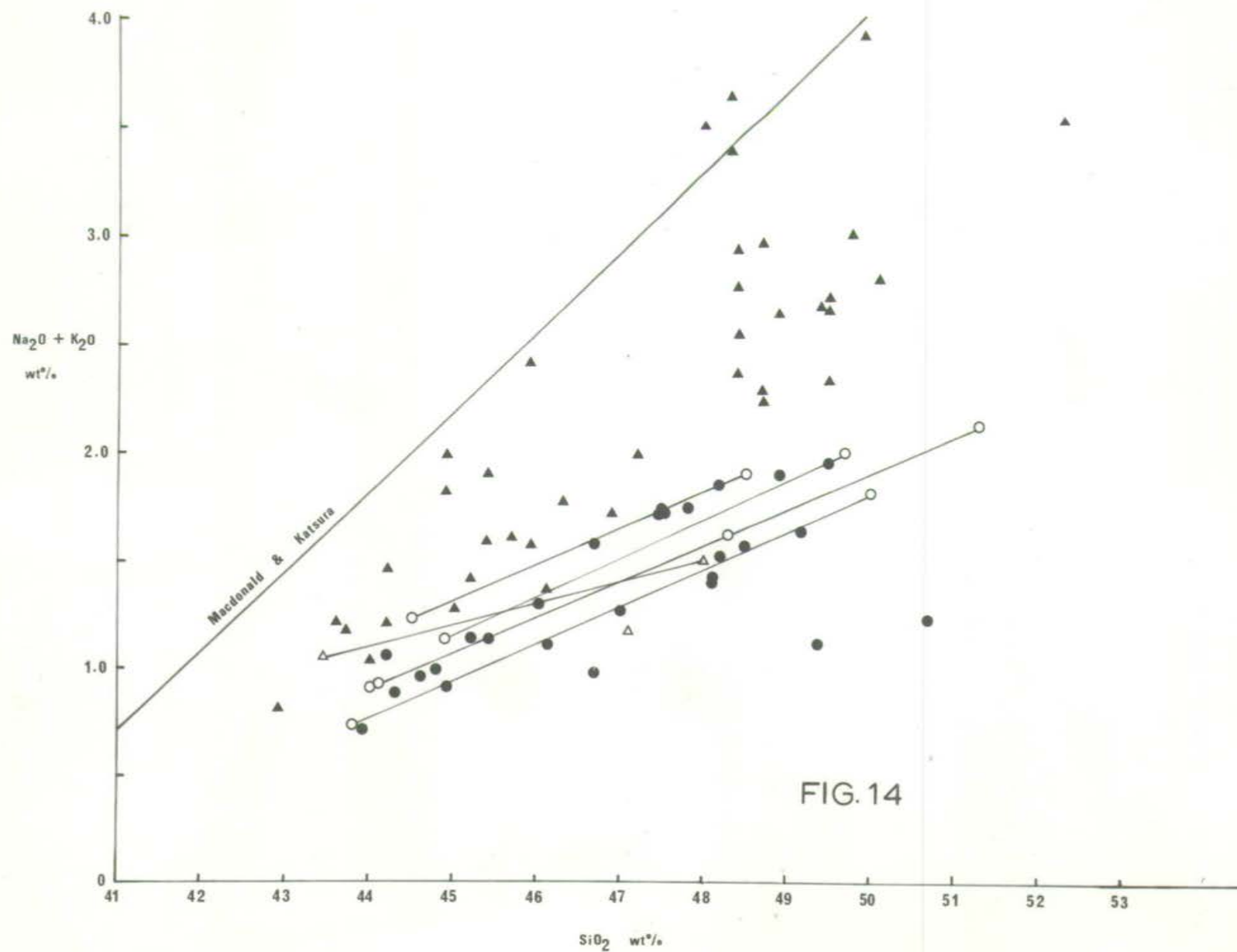


FIG. 12





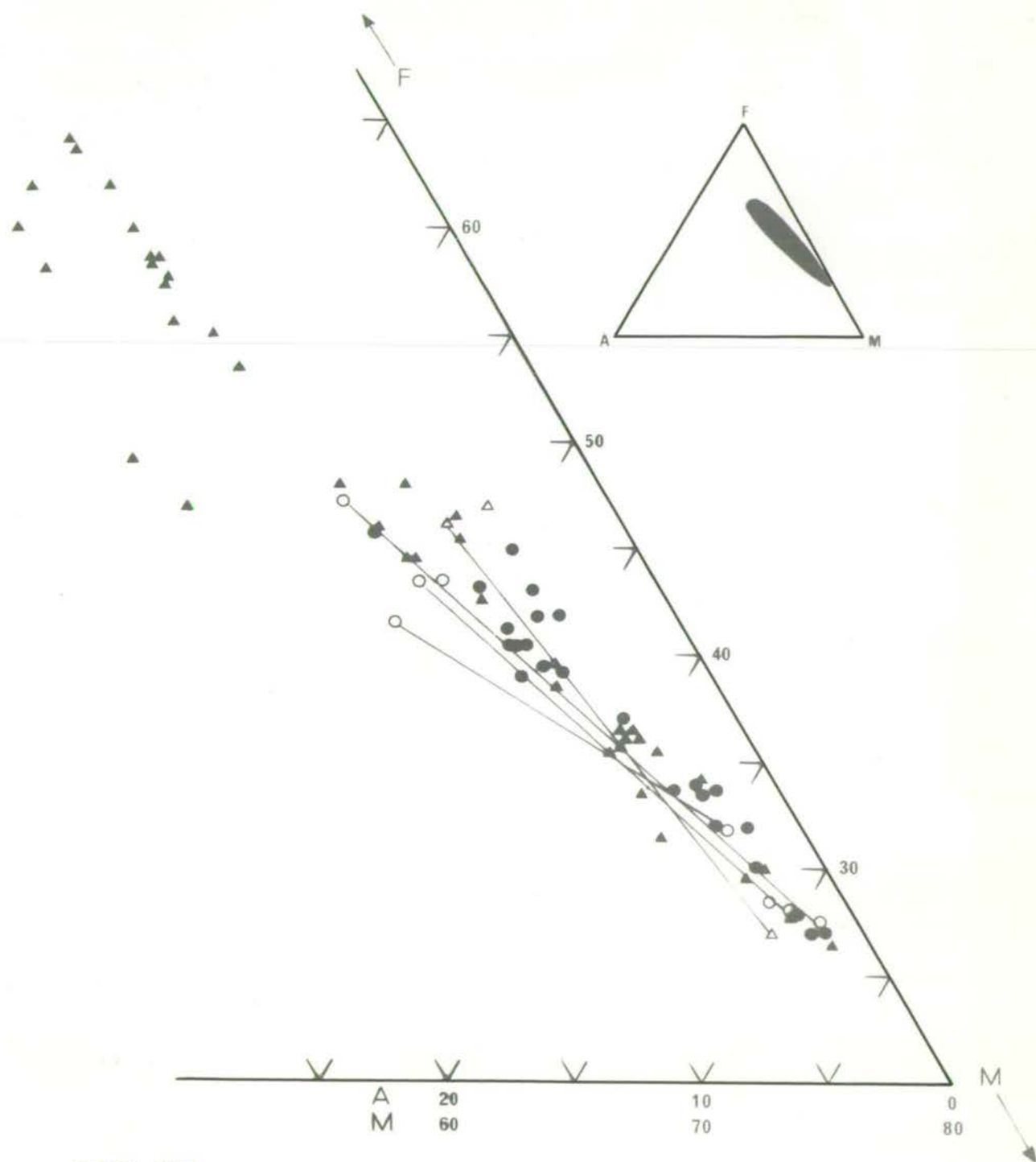


FIG. 15

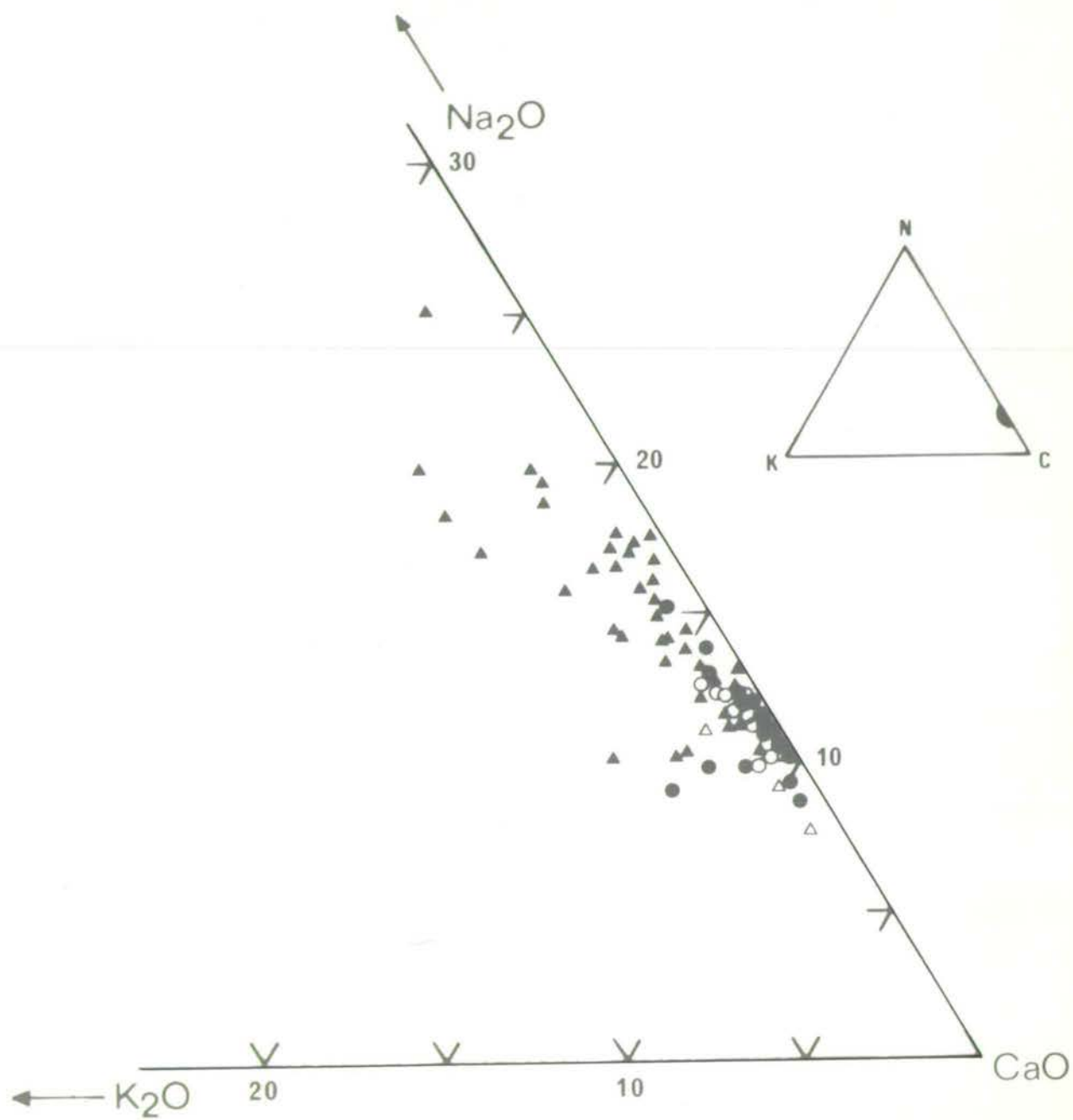
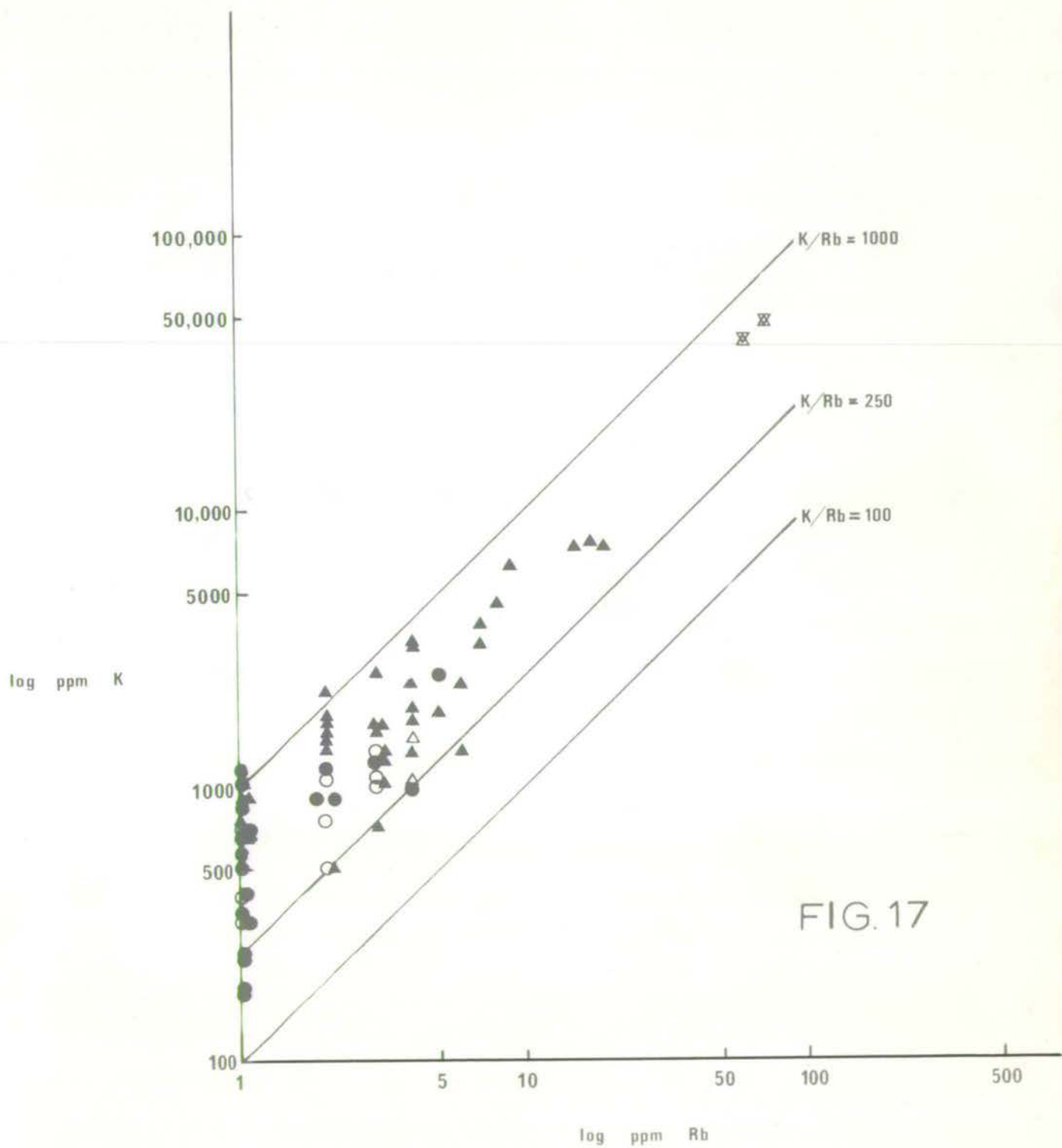


FIG. 16



Chapter 4, which deals exclusively with late-stage differentiation. It is also worthy of note that trends are not easily defined for K_2O , partly because of the extremely low levels involved, with consequent analytical problems, and partly because many compositions appear to have been erratically enriched in K_2O . This departure from linearity for potash is due in part to (i) the reaction of magma with sea-water in the case of the breccias (E-2, RBB, ROB); and (ii) possible sporadic contamination by reaction with acid country rocks, involving addition of K and Rb. These would be among the easiest elements to transfer to the magma, and the effect would be very noticeable when superimposed on the previously low levels of these elements. This erratic behaviour of potash is seen later in Fig. 11.

Fig. 8 illustrates the strong coherence between nickel and magnesium oxide. In a system governed principally by fractional crystallization of forsteritic olivine, both Ni and Mg are quickly removed from the liquid, the Ni occupying Fe^{2+} sites in the growing olivine structures. The correlation coefficient for this pair of elements is 0.99 for Svartenhuk and 0.95 for Baffin Island, indicating a high degree of linearity. Although on this particular diagram it would appear that the Greenland rocks lie at the most primitive (i.e. least evolved) end of the variation (high MgO , high NiO), in this case it might only indicate that there are more compositions represented with strongly cumulative olivine. However, the Ni/Mg ratios for the Greenland rocks are on the average slightly higher than those for Baffin Island, and an explanation will be given later for this difference. The trend of MgO against Ni extrapolated back to approximately 45% MgO , i.e. the concentration in the olivine being removed, gives Ni values for the olivines of approximately 3000 ppm.

The simplest sort of variation diagram involves the plotting of one

element or oxide against another. While this type is of fairly limited value, in this instance it does serve to show the recurrent similarity, not only in absolute values, but also in ratios and trends between the two suites of basalts from Baffin Bay.

Fig. 9 illustrates the relationship between two incompatible, tetravalent, minor elements, Ti and Zr. Zirconium substitutes for titanium when titanium-bearing minerals are crystallizing (Taylor, 1965), but if they are not being formed then both elements tend to remain in the liquid phase. Note the very close coherence of these two elements, the degree of overlap between the two basalt suites and the similarity in the trend of enrichment. This type of relationship, a single overlapping trend with the Baffin Island suite lying at the primitive end of a linear variation, holds true for other pairs of incompatibles such as $K_2O-P_2O_5$, $Ba-P_2O_5$, K_2O-Rb , etc. Fig. 10 again demonstrates this relationship between TiO_2 and P_2O_5 , which are chemically dissimilar but which share a common incompatibility with fractionating phases and therefore show a strong coherence. In these two diagrams the general trend of the tie lines joining intra-flow differentiates, and therefore representing the course of fractionation at 1 atmosphere, lies parallel to the over-all trend in the suites. This might seem to suggest the possibility that all the observed variation is due to near-surface differentiation processes. However, since this enrichment is based on total rejection from crystallizing phases, it does not provide a distinction between fractionation at 1 atmosphere and any other pressure.

In addition to titanium and phosphorus, the other main incompatible element is potassium. With its very large ionic radius (radius $K^+ = 1.33\text{\AA}$), potassium should epitomize the characteristic enrichment of this group of elements in the liquid. Fig. 11 shows a reasonable correlation between

potassium and phosphorus of the same type as in the first two diagrams, but it is marred by the previously discussed erratic behaviour of K_2O .

As mentioned earlier, one of the more notable features of these variation diagrams is the coincidence of the trends drawn for the two suites, with the field of Baffin Island points always lying to the more primitive end of the variation. This feature is approximated in Fig. 12 where a major element oxide, CaO , is plotted against a trace element, Y . Since yttrium normally occupies calcium sites when substituting for a major element but is not taken preferentially over calcium in plagioclase or augite, the ratio Y/CaO in the liquid phase should increase with fractionation. In this diagram there is strong overlap of the two trends at the primitive end of the variation with slightly decreasing Y/CaO ratios. The point of departure comes in the more evolved feldspar-phyric basalts of Svartenhuk which have rapidly increasing Y/CaO ratios.

The relationship between another pair of chemically related elements, calcium and strontium, is represented in Fig. 13. With the exception of the several erratic Baffin Island breccias with high Sr , there is practically no overlap between the suites but rather the parallel arrangement which was evident when calcium was used before in Fig. 12. The diagram, at least, shows the Baffin suite to have a lower Sr/Ca ratio, which is in keeping with the conclusion reached in other figures, i.e. that the Baffin suite is more primitive.

Another case in which a nearly perfect separation has been effected between the two lava suites of Baffin Bay occurs on the total alkalis-silica variation diagram (Fig. 14) which shows that

- 1) the line of Macdonald and Katsura (1964), intended to act as a boundary

between alkalic and tholeiitic basalts, is inapplicable to the rocks of Baffin Bay

- 2) the alkali-silica ratio is lower, i.e. more primitive, in Baffin Island rocks than in those of comparable SiO_2 levels on Svartenhuk
- 3) the evolutionary trends given by the intra-flow differentiates of Baffin Island parallel the main trend
- 4) the two provinces show convergent trends back towards a composition of very low total alkalis and approximately 40% silica, probably olivine; addition and removal of olivine from parental magmas of intermediate composition will produce the observed trends

The familiar A-F-M diagram (Fig. 15) shows two main features: (i) the strong overlap between the two suites, although this feature in itself is no criterion of over-all similarity; and (ii) more significantly, the orientation of the trend towards iron enrichment is very similar in the two suites. The other well-known triangular diagram, $\text{CaO}-\text{Na}_2\text{O}-\text{K}_2\text{O}$ (Fig. 16), serves to demonstrate the strong impoverishment in alkalis, notably K_2O , in Baffin Bay rocks.

IV. K/Rb Ratios

As a result of the work done by Gast (1960, 1965), Engel, Engel and Havens (1965) and Murthey and Stueber (1967), a high K/Rb ratio has become synonymous with primitiveness. Shaw (1968) has reviewed all the available data and has delineated three stages of fractionation based on the rate of decrease of the K/Rb ratios. However, he erroneously states that the ultra-high K/Rb ratios in the range 1000-3500 are shown by "all and only" oceanic tholeiites and achondritic meteorites. For example, the Discovery II

basalts of Muir et al., (1964) have K/Rb averaging less than 300. Also, some of the Baffin Bay basalts almost certainly contain less than the quoted value of 1 ppm. Rb (the lower limit of detection), and therefore some of the K/Rb ratios should rise to well above 1000. (Three samples with the rounded-up value of 1 ppm. Rb and one with 2 ppm. Rb have K/Rb >1000 ; Fig. 17.) This feature suggests a degree of similarity between Baffin Bay basalts and some deep oceanic tholeiites.

K/Rb ratios in the 9 Svartenhuk basalts which contain more than 5 ppm. Rb have been calculated and show a general decrease from a value of 682 in the northeast to 364 in Arfertuarssuk. The two trachytes in Arfertuarssuk (samples 625, 630), which probably represent late-stage derivatives of the basalts, are characterized by the high K/Rb ratios of 651 and 637 respectively. Fractionation trends leading to K/Rb enrichment in siliceous rocks are not unprecedented (Shaw, 1968), but at present the mechanism is imperfectly understood.

Sample 670 gave K/Rb = 221, suggesting that the intrusion of sills in the Qordlortup kua valley and possibly Itsako was a late-stage event in the volcanic history of the province.

V. Recapitulation of Variation Diagrams

It will have been noted in the previous discussion that the Greenland suite is related to the Baffin suite in one of two ways (Fig. 18). In the first case the variation in the two suites combines to form an overlapping linear trend, e.g. when pairs of incompatible trace elements are plotted against one another. In the second instance two parallel trends are generated, as is the case when a trace element is plotted against its related major element or when some combinations of major elements are plotted against one

Fig. 18. Recapitulation of Variation Diagram Types. For explanation, see text.

shaded area = Baffin Island suite.

blank area = Svartenhuk suite.

○ = Baffin Parental Composition

△ = Svartenhuk Parental Composition

IP = low pressure

HP = high pressure

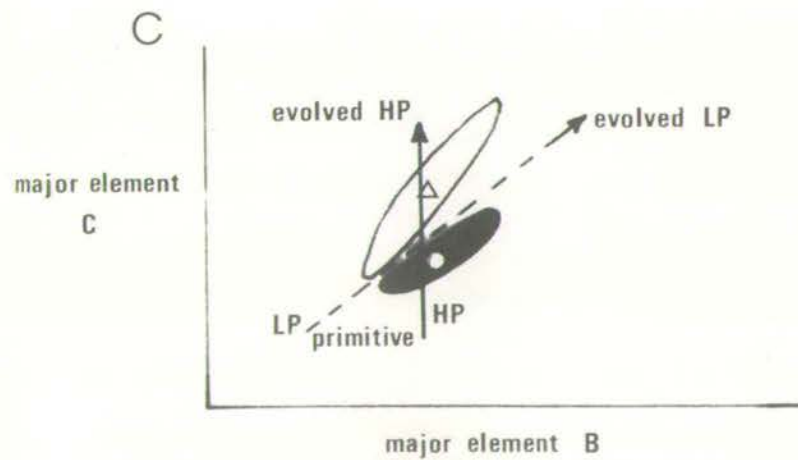
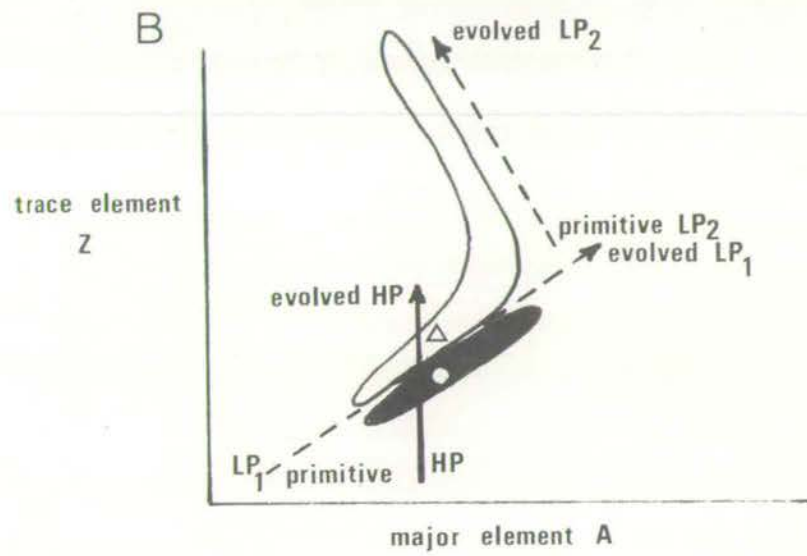
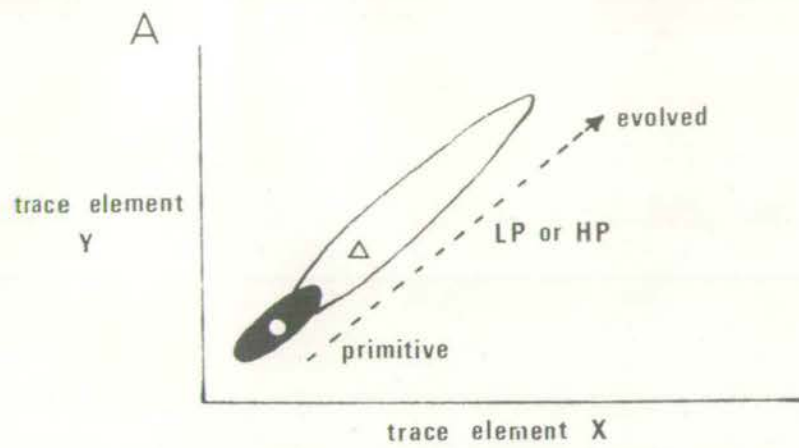


FIG. 18

another. It is proposed to show that there may be no fundamental difference between these types of diagrams and that, in particular, the failure to achieve overlap in the second type does not preclude the two suites being related in exactly the same sense as the first type.

The simplest case involves the plotting of two incompatible trace elements against one another (Fig. 18A). On the diagram the direction of evolution caused by crystal fractionation is shown. These incompatible elements, by definition, increase linearly independently of pressure, although the rate of increase, relative to changes in the major elements, is probably larger during high-pressure eclogite fractionation, when the fractionating phases are close in major element composition to the liquid from which they are being removed (O'Hara and Yoder, 1967). It is therefore impossible to ascertain from this type of diagram the depth at which crystal-liquid fractionation is taking place.

The second case (Fig. 18B) is analogous to the relationship between calcium and yttrium (Fig. 12), in which the early low yttrium basalts are overlapping to a certain extent in a parallel fashion. There can be no doubt that the alignment of the intra-flow differentiation tie lines defines an early low-pressure fractionation trend, almost certainly dictated by removal of olivine (LP_1), in which both Ca and Y are increased in the residual liquid. It is also apparent that once calcic plagioclase becomes a fractionating phase, calcium is depleted in the melt while Y continues to increase (LP_2). However, the original side-by-side configuration of points still remains to be explained. In this particular case, if there had been some slight degree of fractionation at high pressure, i.e. eclogite fractionation, the Ca in the residual liquid would be little changed but the Y would have increased substantially, leading to a higher Y value for later eruptives. This could

well explain the differences in the average incompatible element concentrations between the two suites, where in every instance the "parental" magma on west Greenland is enriched in these elements relative to Baffin Island. This is shown in Table 3, and the method of selecting "parental" compositions is discussed in Chapter 4.

The final example (Fig. 18C) is analogous to the alkali-silica diagram (see Green and Ringwood, 1967, Fig. 8). Again the intra-flow differentiation tie lines define the low pressure effect of olivine removal. The trend of fractionation at high pressure is to increase the alkalis without increasing silica, and therefore material erupted at the surface, having undergone this process at depth, will inevitably show the effects in the form of alkali enrichment. There will therefore appear to be two parental magmas on which the effect of olivine fractionation at low pressure will be to produce a convergent trend in olivine cumulates and a divergent trend in olivine-impoverished compositions.

The conclusion to be drawn from this investigation is that the Baffin lavas were probably erupted first while the potential west Greenland magma fractionated for a while at depth. The effect on the latter was to raise the average level of incompatibles by a factor of 1.5, corresponding to about 35% of eclogite fractionation, all mineralogical traces of which have apparently been lost. It should be pointed out that all three relationships in Fig. 18 could be produced by a greater degree of partial melting of mantle peridotite for the Baffin Island parental magma and then possibly simultaneous eruption of the two batches. It is even conceivable that eruption on Baffin Island post-dated the eruption of the west Greenland material after an interval of further partial melting. These possibilities will be considered in more detail in Chapter 4.

TABLE 3

Comparisons of Incompatible Element Concentrations
in Likely Parental Material

	<u>TiO₂</u>	<u>K₂O</u>	<u>P₂O₅</u>	<u>Zr</u>	<u>Rb</u>	<u>Sr*</u>	<u>Ba</u>	<u>Y</u>	<u>Ga</u>
Baffin	0.77	0.06	0.08	50	1.4	162	40	17	13
Svartenhuk	1.23	0.11	0.14	79	1.6	195	49	18	17
EF Sv/Baf	1.6	1.8	1.8	1.6	1.1	-	1.2	1.1	1.3
Avg. EF Sv/Baf = 1.5									

TiO₂, K₂O and P₂O₅ in weight per cent.; remainder in parts per million.

EF - Enrichment Factor

Sv - Svartenhuk

Baf - Baffin Island

* - Sr includes some erratic values and is not included in the average.

Fig. 19. Histograms Based on Thornton-Tuttle (1960) Differentiation Index.

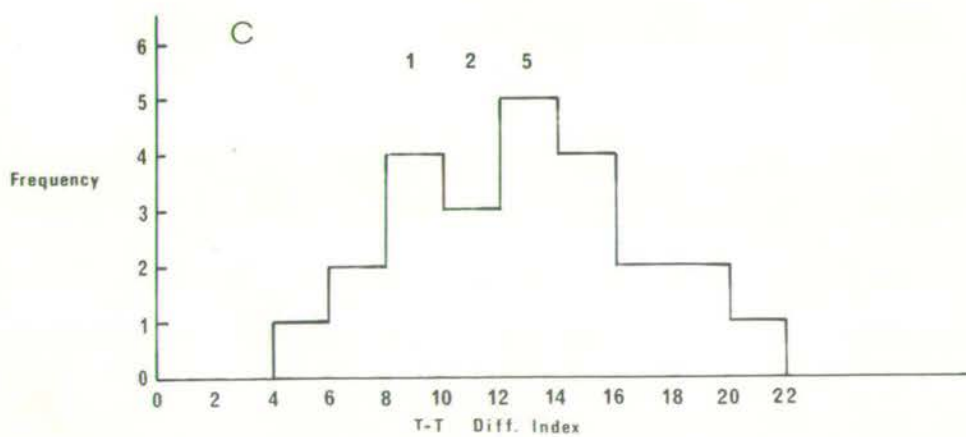
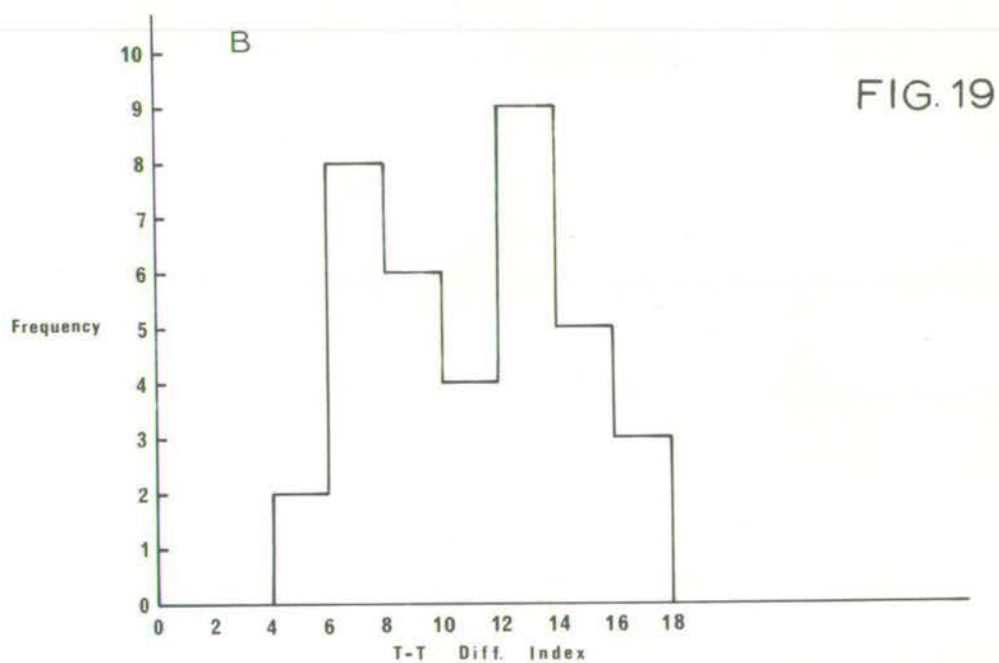
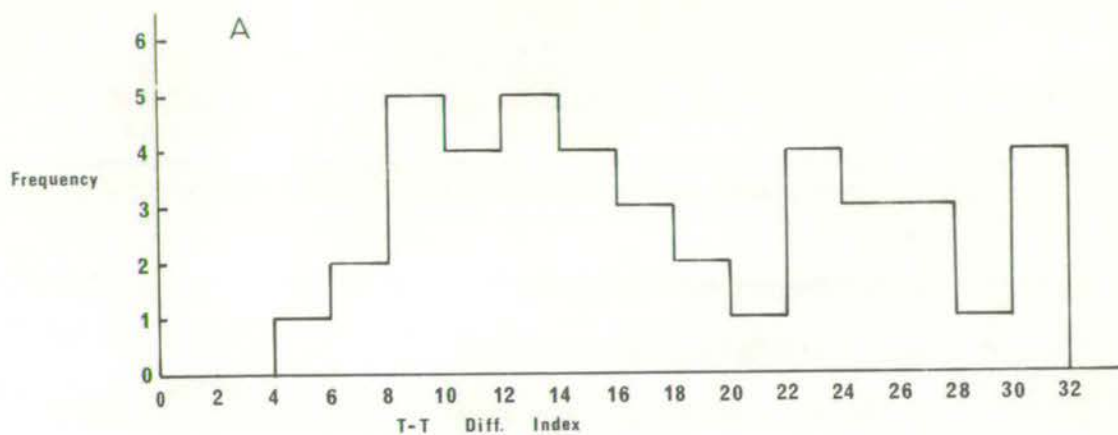
A. 40 Svartenhuk basalts.

B. 37 Baffin Island basalts.

C. 24 Svartenhuk olivine basalts with numbers of possible primary compositions in differentiation index intervals.

D. 24 Baffin Island olivine basalts with numbers of possible primary compositions in differentiation index intervals.

E. 48 Baffin Bay olivine basalts (C + D).



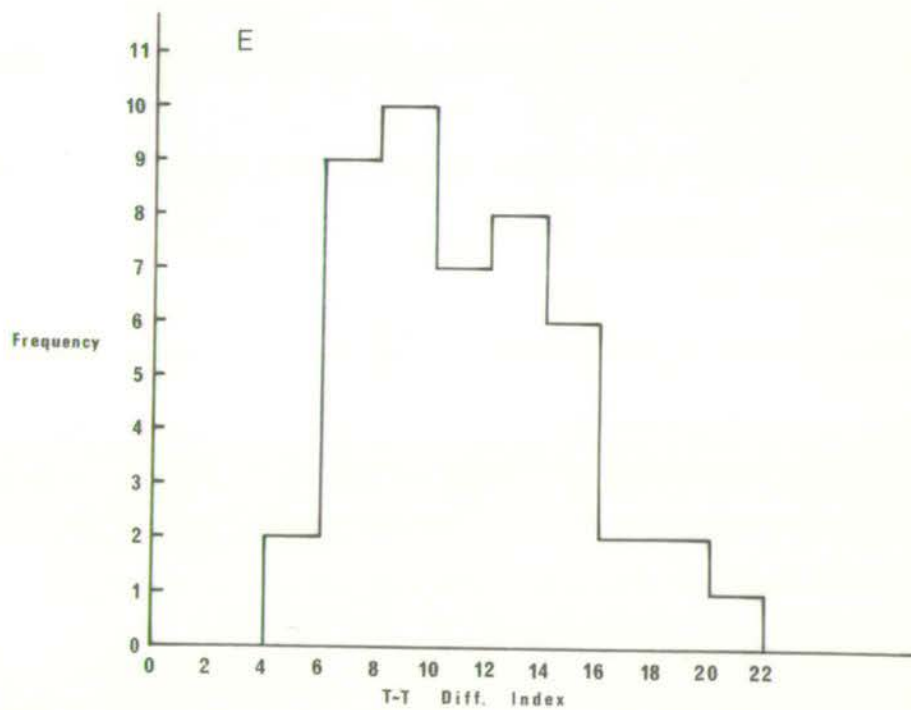
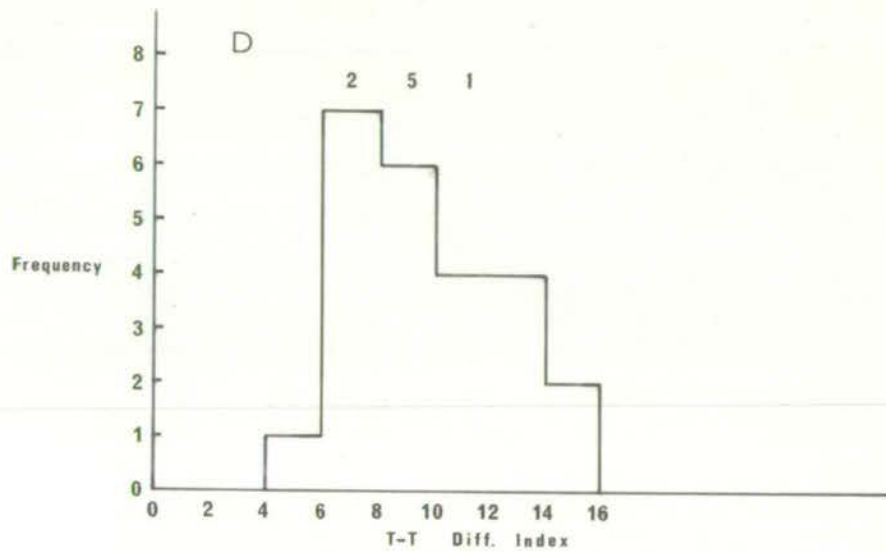


FIG. 19 (cont.)

VI. Statistical Treatment

A) Histograms

The histograms of Fig. 19 illustrate the manner in which selection of chemical analyses for principal components analysis and discriminant function analysis was made. They also show several interesting aspects of the petrographic groupings. The differentiation index of Thornton and Tuttle (1960) was used as the basis of variation because of its inclusion of all the major oxide components and its relative insensitivity to erratic values or errors in determination. It is arguable whether there are sufficient analyses to regard the numbers in certain class intervals as significant; however, several general relationships may be discussed, based on the assumption that sampling of the various rock types has been representative. If there is genuinely an 8 km. thickness of olivine-rich basalts in Svartenhuk, then the frequency of analyses with low differentiation indices is too low in Fig. 19A. The assumption of representative sampling is not valid in the case of the 37 Baffin Island analyses (Fig. 19B); this will be discussed later.

In Fig. 19A there appears to be a trimodal distribution of points in Svartenhuk with peaks at differentiation indices of 10-12, 22-24 and 30-32; these correspond to olivine basalt, normal feldspar-phyric basalt and evolved feldspar-phyric basalt respectively. In addition, there are the two trachytes of Arfertuarssuk, with differentiation indices of 88 and 92, with apparently no representatives between them and the strongly differentiated basalts. This trimodal or, if the trachytes are included, quadrimodal, frequency of occurrence is probably real and, if so, then it points up an interesting feature of the Svartenhuk province as a whole. It would suggest that eruption in Svartenhuk was susceptible to periodic bursts of activity. The continuity of trace element trends across the class-frequency troughs makes it very likely

that these bursts are part of a long differentiation process rather than consisting of new and quite separate magma batches. The initial voluminous outpouring was of olivine-rich basalt which gradually waned to a minimum with corresponding D.I. values in the range 20-22. It is interesting to note that the single analysis in that class-frequency minimum is of the only sill analyzed in the whole suite (sample 670). Fractionation of the non-erupted portion of the initial magma batch may be believed, for the purpose of the present discussion, to have taken place in a magma chamber or conduit until conditions were favourable for renewed eruption. This second phase of activity tapered off at D.I. = 28-30. The third peak is interesting in that it contains not only the expected samples 589 and 638 from the top of the section in Svartenhavn and Arfertuarssuk, respectively, but also samples 661 and 664 from the base of the section on the east coast. (At the same time it should be noted that this same curious juxtaposition also occurs in Fig. 19D, where the two samples with the highest D.I. are E-2 from the very base of the section in Cape Searle and T-55 from the top of a landslipped block on Padloping Island, being probably equivalent to the topmost flow on the undisturbed part of the section.) The explanation offered for this feature, which shows early basalts to be strongly fractionated, is that these may represent the first liquids which came up the conduits and hence have suffered an abnormal degree of heat loss to the surrounding country rock. This extreme cooling, coupled with the possibility of intensive reaction with wall rock at depth (Green and Ringwood, 1967), has led to a chemically evolved appearance in the first eruptives. The magma which immediately followed these initial liquids is imagined to have passed quickly and unmodified through the preheated conduit lined with reaction products.

In order to carry out principal components analysis and discriminant

function analysis, it was considered reasonable to compare only the olivine basalts on Svartenhuk, as the feldspar-phyric basalts are not represented on Baffin Island. By eliminating all 13 feldspar-phyric basalts, 2 within-flow differentiates, the 2 highly evolved specimens from the base of the section and 1 sample analyzed without its zeolites, the number of analyses was dropped from 42 to 24. Similarly, the removal of 6 within-flow differentiates and 2 altered breccias, the reduction of A-5, AA-26 and AA-30 from a single flow at Cape Dyer to an average analysis, and the averaging of the 4 dykes at Cape Searle which fell in the D.I. range 12-14 to one analysis, lowers the original total of 37 analyses also to 24. In the case of the 4 dykes, averaging is justified on the grounds that this number is out of all proportion to the abundance of dykes in the Baffin Island province. As may be seen from the histograms in Figs. 19C, D, to have left these four compositions in might possibly even improve the degree of correlation in the discriminant function analysis.

Written above the differentiation intervals in Figs. 19C, D are the numbers of possible parental compositions (see Chapter 4) in that category. It may be seen that the Baffin Island parental material is more primitive than the Svartenhuk parent (a relation already noted in this chapter), with modes occurring at D.I. values of 8-10 and 12-14 respectively. Both groupings of 24 olivine basalts are roughly unimodal, with the Baffin group being skewed and the Svartenhuk group more nearly approaching a normal distribution. Also, the sum total of 48 Baffin Bay olivine basalts (Fig. 19E) exhibits only a slightly skewed distribution. Thus the prerequisite before F-ratio tests can be applied in the discriminant function analysis is satisfied, namely, the approximation of the arrays of points to normal distributions.

B) Correlation Coefficients

The correlation coefficient, r , is calculated from the formula

$$r = \frac{\sum_{i=1}^N \frac{(x_i - \bar{x})(y_i - \bar{y})}{N \sqrt{s_x^2 s_y^2}}}{N \sqrt{s_x^2 s_y^2}}$$

where x_i is the i^{th} variable in the x array, y_j is the j^{th} variable in the y array, \bar{x} and \bar{y} are the respective means, N the total number of samples and s_x^2 and s_y^2 the variancies of each of the x and y arrays respectively. The value of r can range from (-1) to $(+1)$, i.e. from a perfect negative to a perfect positive correlation. When $r=0$ the two variables are not correlated.

In Table 4 all correlation coefficients in the olivine basalts greater than 0.80 are presented, together with the accompanying coefficient from the other province and that for the feldspar-phyric basalts, even if these are less than 0.80. In a suite of lavas where compositions are controlled by olivine fractionation, strong correlation coefficients are expected between MgO and most other oxides, some varying antipathetically simply because removal of olivine boosts those elements in the liquid not involved in the formation of olivine (e.g. Al_2O_3 , Na_2O , TiO_2 , Zr, Cu, Y, Ga). Others showing strong positive correlations are Ni and Cr, both intimately associated with the olivines or enclosed chromian spinel. Most of the other strong correlations have been discussed elsewhere in Chapter 3. Of particular interest are the strong correlation coefficients associated with yttrium and gallium and especially those involving MgO. Their near-perfect incompatible behaviour is demonstrated later in Figs. 25A, B.

Had the Rb values been higher (they are often below the lower limit of detection of the analytical method used) in the Baffin Island suite, a larger correlation coefficient with K_2O would have been expected. This feature has

Upper coefficient (Baffin Island olivine basalts);
middle coefficient (Svartenhuk olivine basalts);
lower coefficient (Svartenhuk feldspar-phyric basalts).

[illegible]

TABLE 5

Average Analyses and Discriminant Functions

	<u>Avg. B.I.</u>	<u>Avg. Svart.</u>	<u>DF 1</u>	<u>Avg. Kil59</u>	<u>Avg. Kil60</u>	<u>DF 2</u>
SiO ₂	46.2	45.6	3.5	48.3	49.6	-23.1
Al ₂ O ₃	11.0	10.2	0.2	11.6	12.6	4.0
Fe ₂ O ₃	2.9	3.1	16.8	1.8	1.8	15.9
FeO	7.9	8.4	17.2	9.9	9.9	17.9
MgO	19.7	19.4	6.5	13.4	9.9	1.0
CaO	9.4	9.5	11.3	9.9	9.8	17.7
Na ₂ O	1.20	1.47	10.1	1.93	2.33	-4.3
K ₂ O	0.07	0.20	13.4	0.47	0.56	56.0
TiO ₂	0.78	1.25	48.0	2.31	2.81	35.7
P ₂ O ₅	0.09	0.15	-24.0	0.23	0.31	-226.0
MnO	0.18	0.18	-541.7	0.18	0.18	-30.1

- Avg. B.I. - Average of 24 Baffin Island olivine basalts
 Avg. Svart. - Average of 24 Svartenhuk olivine basalts
 DF 1 - Discriminant function for 48 Baffin Bay olivine basalts
 Avg. Kil59 - Average of 23 basalts from the 1959 summit eruption of Kilauea
 Avg. Kil60 - Average of 17 basalts from the 1960 flank eruption of Kilauea
 DF 2 - Discriminant function for 40 Kilauean basalts erupted in 1959-60

TABLE 6

Summary of Discriminant Function Analysis

Population	Sub-Population	Sample Size	Range of Discriminant Index	Mean Discriminant Index	F-Ratio
Baffin Bay	Baffin Island	24	520-540	531	32.7
	Svartenhuk	24	554-590	569	
Kilauea	Summit, 1959	23	(-640)-(-624)	-630	15.9
	Flank, 1960	17	(-665)-(-641)	-655	

been demonstrated in Fig. 17. However, when these two incompatible elements rise to higher levels, strong correlation coefficients are generated (see section on late-stage differentiation in Chapter 4).

In short, all the high correlation coefficients agree with the theory of fractionation of olivine alone during the initial stages.

C) Discriminant Function Analysis

Discriminant function analysis is concerned with properly identifying the origin of a sample on the basis of certain measurable characteristics. Chayes (1964, 1965) and Chayes and Metais (1964) have been concerned with the environment of derivation of various suites of rocks, notably an attempt to distinguish between oceanic and circum-oceanic basalts. Although the geographical significance of such a discrimination is no longer valid, the discriminant function is still useful for classifying "magma-types".

The question arises in the study of these basalts as to whether it is possible to find a discriminant function which will correctly assign an unlabelled analysis to one side of Baffin Bay or the other. It was hoped that the inability to find a flat with a low density of points between the two suites in 11-dimensional Euclidian space could be construed as the paramount argument in favour of regarding these basalts as having been randomly derived from one statistical population, or in geological terms, petrographic province. The arguments involved in selecting the discriminant function are discussed by Krumbein and Graybill (1965).

The discriminant function for the 48 olivine basalts of Baffin Bay, DF1, is given by a vector of discriminant coefficients in Table 5. In order to obtain the discriminant index of any analysis, each oxide is multiplied by the corresponding discriminant coefficient, and the cross-products are summed and compared with an arbitrary boundary value.

The results of the discriminant function analysis are summarized in Table 6. In the case of the 48 Baffin olivine basalts a perfect separation was effected between the two suites through application of the discriminant function, DF1. The value of the F-ratio was so large as to force a rejection of the null hypothesis, i.e. the mean discriminant index of Baffin Island equals the mean discriminant index of Svartehuk. In a control case where 23 analyses of material from the summit eruption of Kilauea in 1959 were compared with 17 analyses of material erupted on the flank of the same volcano in 1960 (analyses taken without bias from Murata and Richter, 1966), the discriminant function, DF2, of Table 5 was obtained. The results are summarized in Table 6, which shows again a perfect separation of the two sub-populations and an F-ratio so large as to force again rejection of the null hypothesis.

What may be deduced from this analysis? First, it has produced an unbiased and purely statistical assessment of the probability that each pair of samples may be regarded as having been derived from one population. In both cases the statistical verdict is negative. Second, it has provided potentially useful functions for cataloguing analyses of unknown material. But most important, the Kilauean test case has demonstrated that statistical rejection of identity does not preclude a rational geological explanation of derivation or relation and does not preclude geographical association. There is nothing in this statement which is not already intuitively known about all igneous provinces. In the case of the Hawaiian material, the 1960 flank eruption has been regarded by Murata and Richter (1966) as a mixing of the summit magma with a "rest liquid" from an earlier eruption of Kilauea, the latter having evolved by means of crystal-liquid fractionation in a high level magma chamber. In the case of the Baffin Bay basalts it has already been suggested that the observed differences between the suites might be attributable

to eclogite fractionation. It is now proposed to test this hypothesis further by means of principal components analysis.

D) Principal Components Analysis

(1) Method

A simple explanation of the method of calculating principal components is given by Hope (1967), and a geochemical application of this method has been demonstrated by Le Maitre (1968). In essence, the method permits simultaneous examination of variation in any number of variables, in this case the 11 major oxides of basalts. For example, in the Baffin Island suite of olivine basalts the 24 analyses, each consisting of 11 oxides, can be regarded as a distribution of 24 points in 11-dimensional Euclidian space defined by 11 orthogonal axes. Principal components analysis examines this distribution and extracts a line corresponding to the direction of maximum spread of the points; i.e. the sum of squares of the distances of all the points from a 10-dimensional flat is a maximum. The first principal component is then a vector perpendicular to this hyperplane, i.e. the best straight line fit in 11-dimensional hyperspace. Once the first principal component has been extracted from the distribution, the method then selects the direction of the largest remaining spread of points perpendicular to the first axis in exactly the same manner. This direction is termed the second principal component. The method continues until all the variation is accounted for in a new set of 11 orthogonal vectors, each successive vector accounting for progressively less and less of the total variance in the 24 samples.

(2) Results

The first four principal components, which are just functions of the

original analyses, are given in Table 7 for both groups of 24 olivine basalts and the combination of all 48 olivine basalt analyses. Note that the first four principal components in Table 7 account for 92.5% and 94.8% of the total variance in Baffin Island and Svartenhuk respectively. When the 48 analyses are combined as a group, the first four principal components still account for 92.5% of the total variance. Also note that in each case heavy positive weighting is given in the first principal component to FeO and MgO, which largely control the rest of the variation by their removal in the formation of olivine.

When all 48 Baffin Bay olivine basalts are taken as a group and plotted on a principal latent vector variation diagram (Le Maitre, 1968), the axes of the diagram will no longer account for the maximum variation in each of the provinces. However, the alternative of trying to make comparisons of diagrams with slightly differently oriented axes is not possible. In Fig. 20 only the centroid is shown for each province.

(3) Interpretation

Earlier in Chapter 3 it was suggested that the cause of the somewhat more evolved appearance of the Svartenhuk basalts, especially as regards the levels of the incompatible elements, may have been due to a brief period of eclogite fractionation while the magma was being held at depth prior to eruption. This theory is substantiated in the six principal latent vector variation diagrams involving all combinations of the first four principal components, which account for 92.5% of the total sample variance. In these it is seen that a modest removal of the biminerallitic eclogite pair, omphacite plus pyrope, or the average biminerallitic eclogite from kimberlite (Kushiro and Aoki, 1968), could effect a shift of the Baffin centroid so as to coincide with that of Svartenhuk.

TABLE 7

Variances and Eigenvectors of Principal Components

	FIRST PRINCIPAL COMPONENT			SECOND PRINCIPAL COMPONENT			THIRD PRINCIPAL COMPONENT			FOURTH PRINCIPAL COMPONENT		
Location	Baffin	Svartenhuk	Combined	Baffin	Svartenhuk	Combined	Baffin	Svartenhuk	Combined	Baffin	Svartenhuk	Combined
Percent of Total Variance Accounted for	69.5	56.1	54.0	11.0	17.6	18.2	6.4	13.8	12.0	5.6	7.3	8.3
SiO ₂	-0.336	-0.378	-0.357	+0.099	-0.037	+0.225	+0.042	-0.181	+0.223	-0.296	+0.123	+0.056
Al ₂ O ₃	-0.349	-0.394	-0.375	+0.141	+0.002	+0.199	+0.182	-0.072	+0.200	-0.038	+0.079	+0.109
Fe ₂ O ₃	-0.299	+0.008	-0.207	-0.255	+0.602	+0.168	-0.073	+0.323	-0.654	-0.421	+0.369	+0.227
FeO	+0.324	+0.105	+0.234	+0.067	-0.659	-0.393	+0.141	-0.180	0.484	+0.249	+0.024	-0.110
MgO	+0.350	+0.399	+0.397	-0.121	+0.023	-0.071	-0.184	+0.038	-0.177	+0.029	-0.063	-0.079
CaO	-0.331	-0.384	-0.382	+0.224	+0.009	+0.067	+0.269	+0.029	+0.158	+0.095	+0.018	+0.091
Na ₂ O	-0.330	-0.374	-0.370	+0.086	+0.015	-0.104	+0.011	-0.199	+0.156	+0.106	-0.027	-0.185
K ₂ O	-0.154	-0.060	-0.093	-0.699	-0.185	-0.542	-0.361	+0.677	-0.280	-0.118	-0.470	+0.265
TiO ₂	-0.338	-0.381	-0.317	-0.081	-0.049	-0.373	+0.135	-0.005	+0.002	+0.210	+0.006	-0.110
P ₂ O ₅	-0.253	-0.306	-0.250	-0.304	-0.111	-0.523	-0.071	+0.433	-0.109	+0.763	-0.135	+0.056
MnO	+0.169	+0.034	+0.152	-0.491	-0.391	-0.017	+0.824	+0.370	+0.280	-0.103	+0.773	+0.887

Fig. 20. Principal Latent Vector Variation Diagrams (after Le Maitre, 1968).

● Average of 24 Baffin Island olivine basalts.

▲ Average of 24 Svartenhuk olivine basalts.

□ Average of 6 biminerallitic eclogites from Kimberlite (Kushiro and Aoki, 1968).

1 Pyrope (Deer et al., 1962. Vol. 1, Table 17 Anal. 1).

2 Pyrope (Deer et al., 1962. Vol. 1, Table 17 Anal. 2).

3 Omphacite (Deer et al., 1962. Vol. 2, Table 23 Anal. 1).

4 Omphacite (Deer et al., 1962. Vol. 2, Table 23 Anal. 5).

5 Labradorite (Deer et al., 1962. Vol. 4, Table 16 Anal. 11, 14).

6 Olivine (Deer et al., 1962. Vol. 1, Table 2 Anal. 10).

7 Olivine (Deer et al., 1962. Vol. 1, Table 2 Anal. 12).

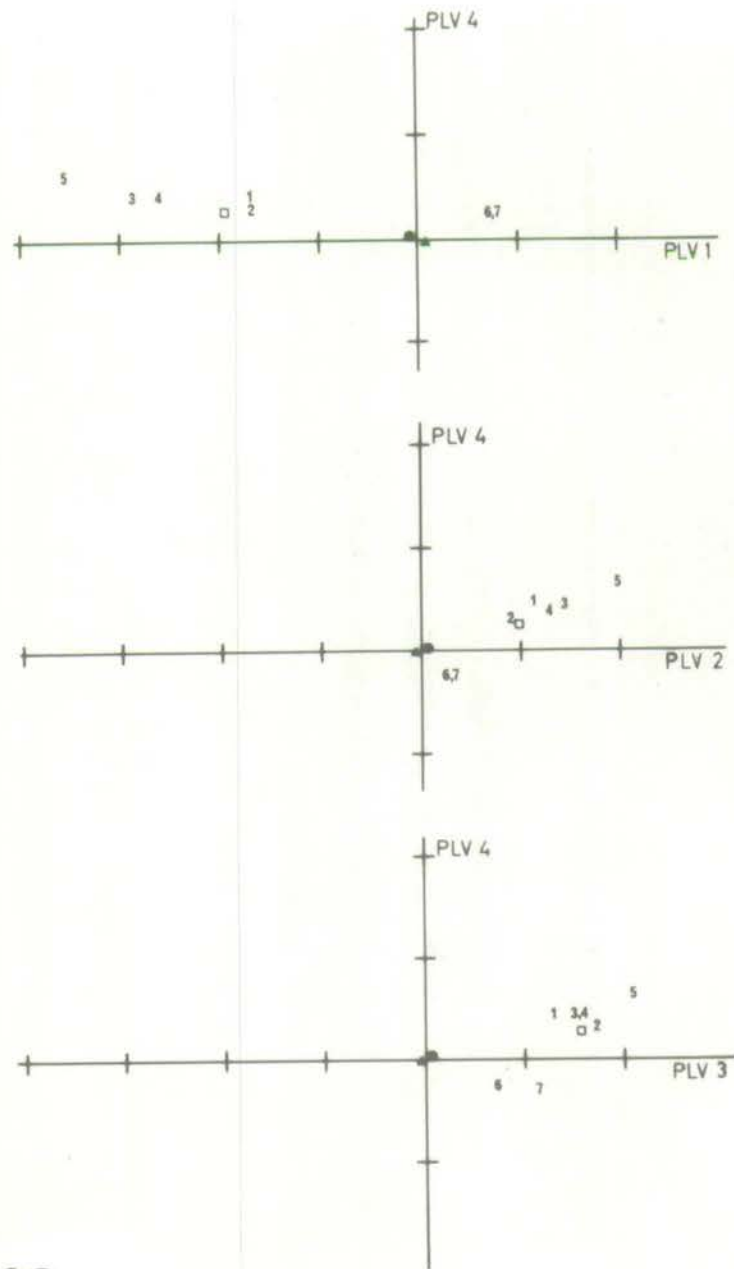
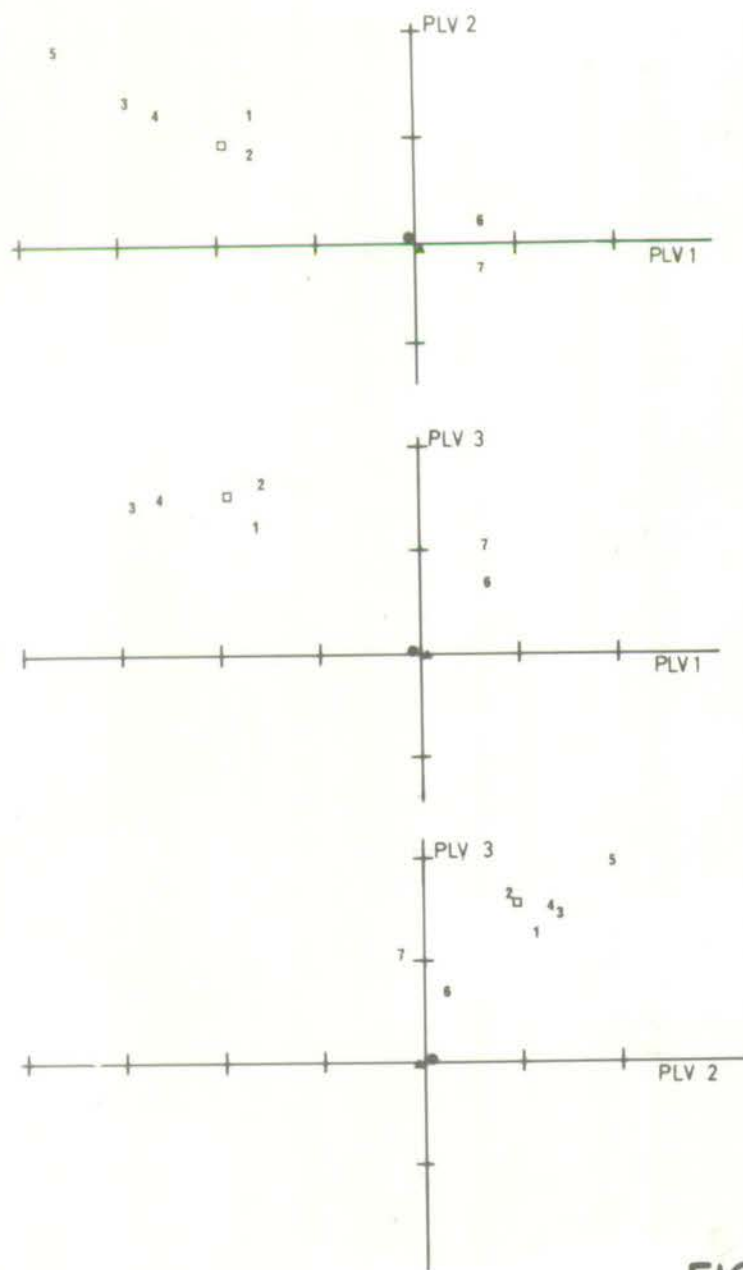


FIG. 20

In Fig. 7A, B it was noted that the Svartenhuk suite as a whole is poorer in SiO_2 , Al_2O_3 and Na_2O but richer in total iron and Fe/Mg than the Baffin group. These differences in the major elements can be generated by a slight preferential removal of garnet over omphacite from the Baffin parental magma. A further predictable effect of eclogite fractionation is an increase of the CaO/MgO and decrease of the $\text{Na}_2\text{O/K}_2\text{O}$ ratios in the residual liquids (O'Hara and Yoder, 1967, Fig. 5). These ratios are 0.48 and 7.8 for the 24 Baffin olivine basalts and 0.49 and 7.3 for the 24 Svartenhuk olivine basalts, respectively. Although the difference in CaO/MgO is probably not statistically significant, at least the direction of change is in agreement with predicted variation if eclogite fractionation has been in operation. During eclogite fractionation in which no olivine is being removed, it may also be possible for Ni and Ni/Mg to increase; the higher ratio is a feature of the Svartenhuk basalts (Fig. 8).

At this point the warning of Le Maitre (1968) should be kept in mind, i.e. "as there are an infinite number of solutions of what must be added to or subtracted from one composition to produce another, the presentation of a mathematically correct solution is not, by itself, conclusive proof that such a process is geologically valid". Therefore eclogite fractionation is not proven but remains within the realm of possibility as a mechanism for raising the level of the incompatible minor elements without greatly affecting the major element chemistry.

VII. Comparison of Analyses

The usual practice of comparing whole rock analyses has been resisted on the grounds that major element chemistry is too dependent on modal per cent. and type of phenocryst phases as well as the entire, complex history of

fractional crystallization. Instead, it is proposed that comparisons be restricted to the incompatible oxides and trace elements. These oxides are also susceptible to wide variation caused by the degree of partial melting of the mantle as well as by the type and extent of subsequent fractionation, but throughout both of these processes (except in the first few per cents. of partial melting which are probably not represented at the surface) the behaviour of the incompatibles should be nearly linear. Contamination can also have a profound influence and may produce departure from linearity and yet, in spite of these problems, it is evident from the data in Table 8 that each tholeiitic province has a unique assemblage of incompatibles, representing the sum total of all the effects operative in that province. For instance, the incompatible element "fingerprint" of Hawaii is characterized by high TiO_2 (Macdonald and Katsura, 1964), whereas those of the Nuanetsi and Northern Karroo areas (Cox et al., 1967) show high K_2O , and because of such pronounced features these groups are distinguishable from other provinces.

Engel, Engel and Havens (1965) have classified the deep oceanic tholeiites as primary magmas on the basis of their low incompatible elements, their high Na/K and K/Rb ratios and their low Sr87/86 ratios. In Table 8 the best matched of the incompatible groups from different environments is that of Svartenhuk with the deep oceanic tholeiites (rows 2 and 4). It has already been demonstrated elsewhere in this chapter that the Baffin Island suite tends to lie at the primitive end of any variation trend, and the average (Table 8) repeats the claim for a parent-daughter relationship with the Svartenhuk lavas. In passing, it is worth noting the degree of similarity between the Svartenhuk basalts and the Skaergaard marginal chill (rows 2 and 11), raising the interesting question of a possible relationship between east and west Greenland Tertiary magmas.

TABLE 8

Comparison of Incompatible Minor Elements in Tholeiites

	<u>TiO₂</u>	<u>K₂O</u>	<u>P₂O₅</u>	
1.	0.78	0.07	0.09	} Baffin Bay
2.	1.25	0.20	0.15	
3.	2.29	0.39	0.26	
4.	1.36	0.16	0.13	} Deep Oceanic Tholeiites
5.	1.60	0.18	0.12	
6.	1.40	0.49	0.19	
7.	2.09	0.13	0.22	} Hawaii
8.	2.50	0.38	0.26	
9.	0.45	0.24	0.09	} Chilled Margins of Major Intrusions
10.	0.34	0.14	0.09	
11.	1.40	0.19	0.07	
12.	0.57	0.64	0.18	} Antarctic Dolerites
13.	0.80	0.80	0.14	
14.	1.47	0.64	0.20	} Continental Tholeiites
15.	2.69	1.59	0.41	
16.	3.01	1.62	0.48	
17.	1.13	0.74	0.13	
18.	2.68	0.57	0.36	
19.	1.77	1.02	0.22	

1. Avg. 24 Baffin Island olivine basalts (Table 5).
2. Avg. 24 Svartenhuk olivine basalts (Table 5).
3. Avg. 15 Svartenhuk feldspar-phyric basalts.
4. Avg. 21 deep oceanic tholeiites (Nicholls et al., 1964; Engel, Engel and Havens, 1965; Engel, Fischer and Engel, 1965).
5. Avg. 9 mid-Atlantic ridge basalts from Atlantis Expedition at 30°N. (Muir et al., 1966).
6. Avg. 8 mid-Atlantic ridge basalts from Discovery II Expedition at 45°N. (Muir et al., 1964).
7. Avg. 13 tholeiites from Palolu, Hawaii (Macdonald and Katsura, 1964).
8. Avg. 181 tholeiites from Hawaii (Macdonald and Katsura, 1964).
9. Stillwater chilled margin (Hess, 1960).
10. Bushveld chilled margin (Hess, 1960).
11. Skaergaard chilled margin (Hess, 1960).
12. Avg. 5 dolerites from Ferrar, Antarctica (Gunn, 1966).
13. Avg. 21 chilled diabbases from Antarctica (Hamilton, 1965).
14. Avg. Cascade basalt (Carmichael, 1964).
15. Avg. 42 'limburgites' from Nuanetsi (Jamieson, pers. comm.).
16. Avg. 29 basalts from Northern Province, Karroo (Cox et al., 1967).
17. Avg. 21 basalts from Basutoland (Cox and Hornung, 1966).
18. Avg. 12 lower Deccan traps (West, 1958; Sukheswala and Poldervaart, 1958).
19. Avg. 21 upper Deccan traps (Sukheswala and Poldervaart, 1958).

TABLE 9

Comparison of Incompatible Trace Elements in Tholeiites

	<u>Ba</u>	<u>Ga</u>	<u>Rb</u>	<u>Sr</u>	<u>Y</u>	<u>Zr</u>
1.	49	13	1.3	126	17	55
2.	69	16	3.6	215	19	82
3.	143	23	5.9	285	33	156
4.	15	18	<10	120	44	97
5.	234	11	17	280	-	51
6.	780	-	32	850	-	297
7.	772	-	45	726	-	314
8.	256	16	<50	190	23	85

1. Avg. 24 Baffin Island olivine basalts.
2. Avg. 24 Svartenhuk olivine basalts.
3. Avg. 15 Svartenhuk feldspar-phyric basalts.
4. Avg. 15 deep oceanic tholeiites (Engel, Engel and Havens, 1965; Engel, Fischer and Engel, 1965).
5. Avg. 7 mid-Atlantic ridge basalts from Discovery II Expedition at 45°N. (Muir et al., 1964).
6. Avg. 42 'limburgites' from Nuanetsi (Jamieson, pers. comm.).
7. Avg. 29 basalts from Northern Province, Karroo (Cox et al., 1967).
8. Avg. 21 basalts from Basutoland (Cox and Hornung, 1966).

The comparison of incompatible trace elements (Table 9) becomes much more difficult because of the lack of reliable data. Not enough provinces are represented, but on the whole it is seen that the general tenor of the Baffin Bay incompatibles is very low. However, clear-cut distinctions between groups are not as obvious as in Table 8. When dealing with elements in the parts-per-million range, it is probably necessary to consider the added effect of mantle inhomogeny, for which there appears to be other evidence (Gast et al., 1964; Powell et al., 1965; Green and Ringwood, 1967). In some of the provinces where the incompatible trace elements are very high, eclogite fractionation may have been very important prior to eruption of the magma (O'Hara and Yoder, 1967).

The conclusion to be drawn from the comparative tables is simply that the two suites of Baffin Bay basalts are similar and, at the same time, sufficiently distinct from other comagmatic provinces to suggest that they may belong to a single petrological province characterized by low levels of incompatible elements.



I. Introduction

The problem of basalt petrogenesis is one that has received considerable attention, especially in the last decade. Since 1957 each Year Book from the Geophysical Laboratory in Washington has added more relevant and increasingly sophisticated information towards the solution of this particular problem. Gradually other experimental laboratories have followed suit, and, although the ultimate solution has not been reached, nevertheless increasingly severe limitations are being placed on wildly speculative theories.

This chapter will deal first with projections of the basalt compositions in the simple normative basalt tetrahedron at atmospheric pressure. A section is then devoted to reviewing both the case made for regarding the upper mantle as consisting of garnet peridotite and the reasons for believing that at high pressure such a rock will yield a hypersthene-normative picritic liquid on partial melting. The Baffin Bay basalts are then plotted in the modified lime-magnesia-alumina-silica (CMAS) tetrahedral projection, and the chapter concludes with a discussion of their petrogenesis.

II. Simple Normative Basalt Tetrahedron

Most of the variation diagrams in Chapter 3 would suggest that to explain the genesis of the suite of Baffin Island basalts is to explain the origin of both suites. However, those diagrams were based mainly on selected pairs of elements and may therefore have been unrepresentative of the bulk rock compositions. A diagram which involves all the major components would be more desirable, and this is to be found in the form of the normative basalt tetrahedron similar to those first used by Tilley (1961) and Coombs (1963). In this case the CIPW normative constituents (weight per cent.) are plotted at

the four corners of the tetrahedron in the following manner:

Olivine = normative (forsterite + fayalite) + olivine component of
normative hypersthene

Clinopyroxene = normative clinopyroxene

Plagioclase = normative (albite + anorthite)

Quartz = normative quartz + quartz component of normative hypersthene

Projections are given from all corners of the tetrahedron. In three cases the 1 atmosphere dry "cotectics" (lying on the lower surface of the primary phase volume of the projecting phase) of the synthetic system, Fo-Di-An-Qz, and the "natural" system, Oliv-Cpx-Plag-Qz, are shown. Thus, the liquid surface bounding the primary phase volume of the projecting phase is being projected onto the base of the tetrahedron. The abbreviation "cotectic" when referring to the "natural" system will be used throughout to denote the locus of liquid compositions in equilibrium with the phase from which each projection is made, plus the two other phases indicated on the diagram. The natural cotectics have been obtained by plotting, in each projection, published basalts with experimentally investigated phase relations and from these constructing the partial pseudo-quaternary phase diagrams. Most of the experimental work has been done by Tilley et al. (1963, 1964, 1965, 1967), although a few data points have been obtained from the work of Kuno (1965) and Green and Ringwood (1967).

A) Olivine Projection (Fig. 21)

If the observed variation in these rocks is controlled mainly by olivine fractionation, as has been suggested by Fig. 7, then a view of the variation from the olivine corner of the tetrahedron should reveal a strong clustering

Fig. 21. Simple Normative Basalt Tetrahedron, Olivine Projection.

Fig. 22. Simple Normative Basalt Tetrahedron, Clinopyroxene Projection.

Fig. 23. Simple Normative Basalt Tetrahedron, Plagioclase Projection.

Fig. 24. Simple Normative Basalt Tetrahedron, Quartz Projection.

Ornamentation as in Fig. 7.

Solid Lines - Univariant equilibria in the synthetic system

Fo-Di-An-SiO₂, except Fig. 24, where synthetic system represented is Fo-Di-An.

Broken Lines - Pseudo-univariant equilibria in the natural

system Oliv-Cpx-Plag-Qz as determined from melting relations of basalts.

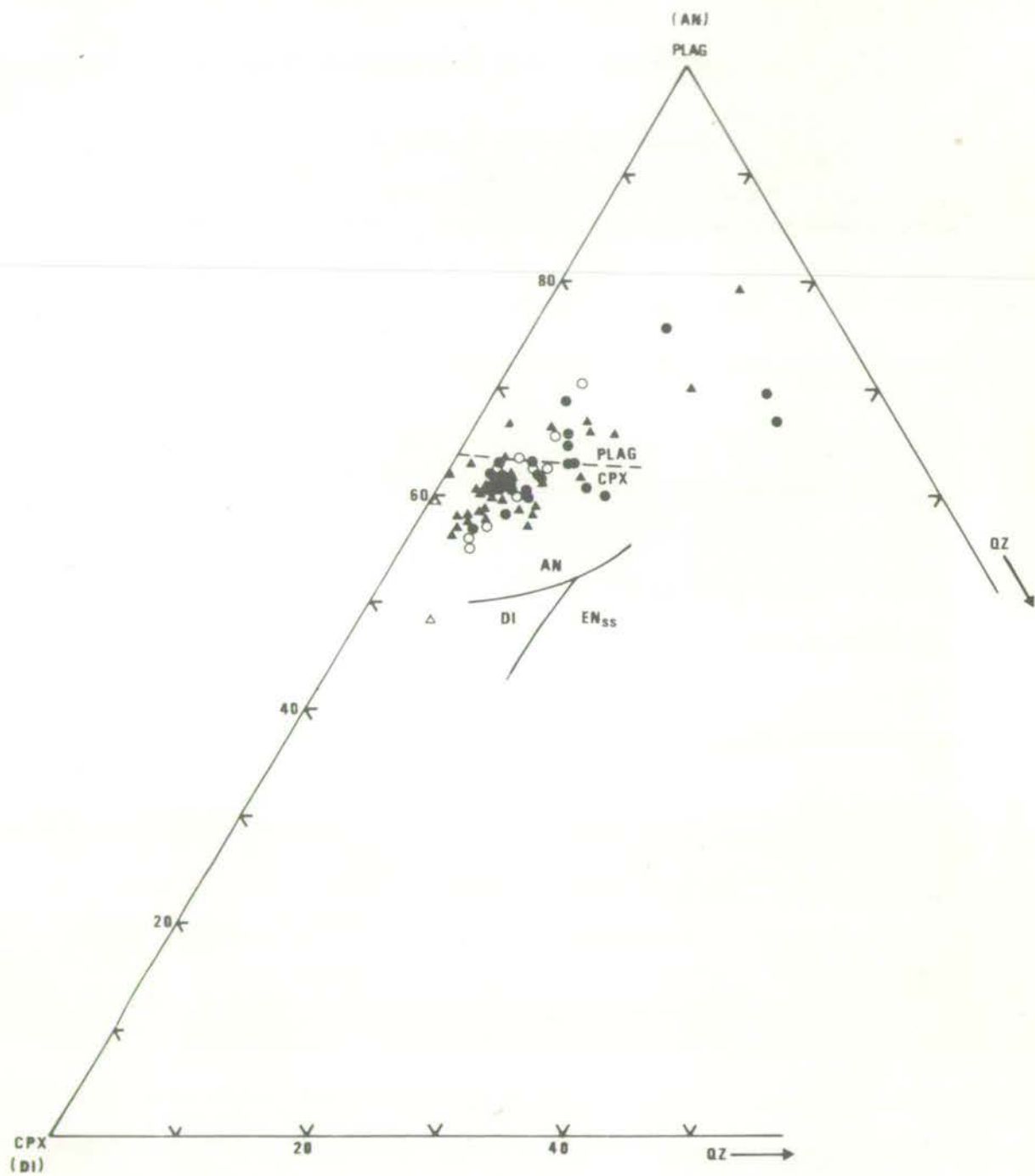


FIG. 21

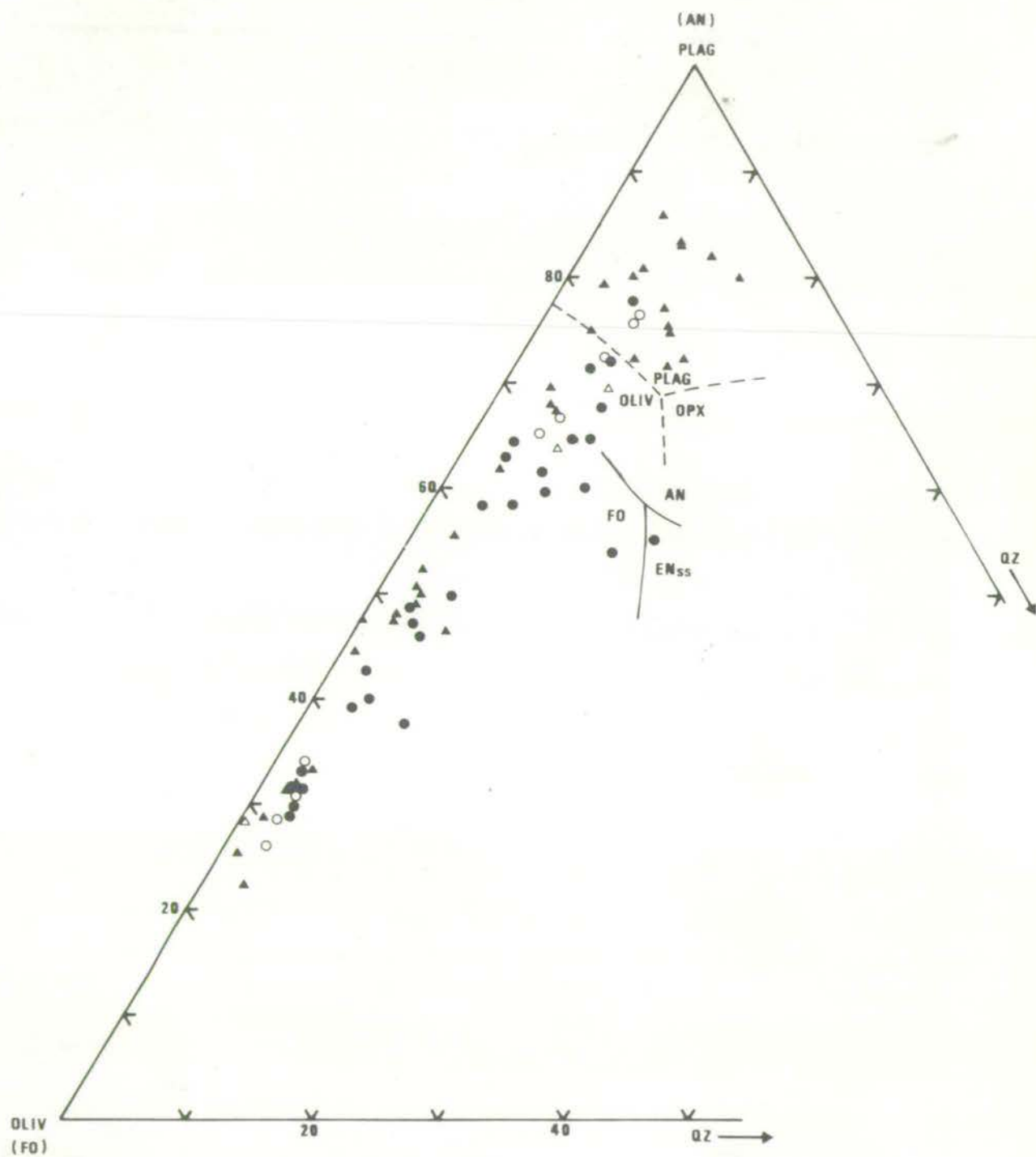


FIG. 22

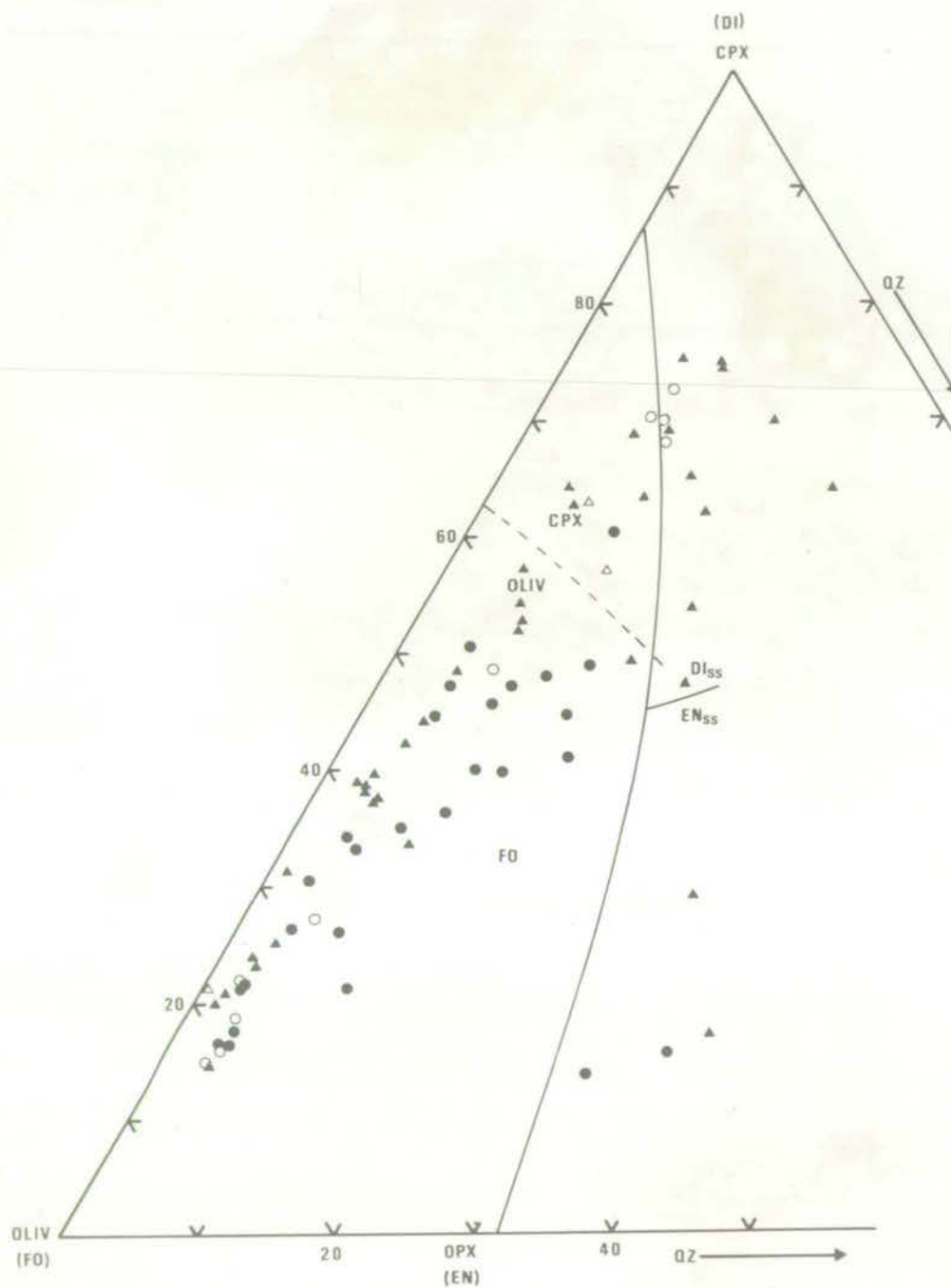


FIG. 23

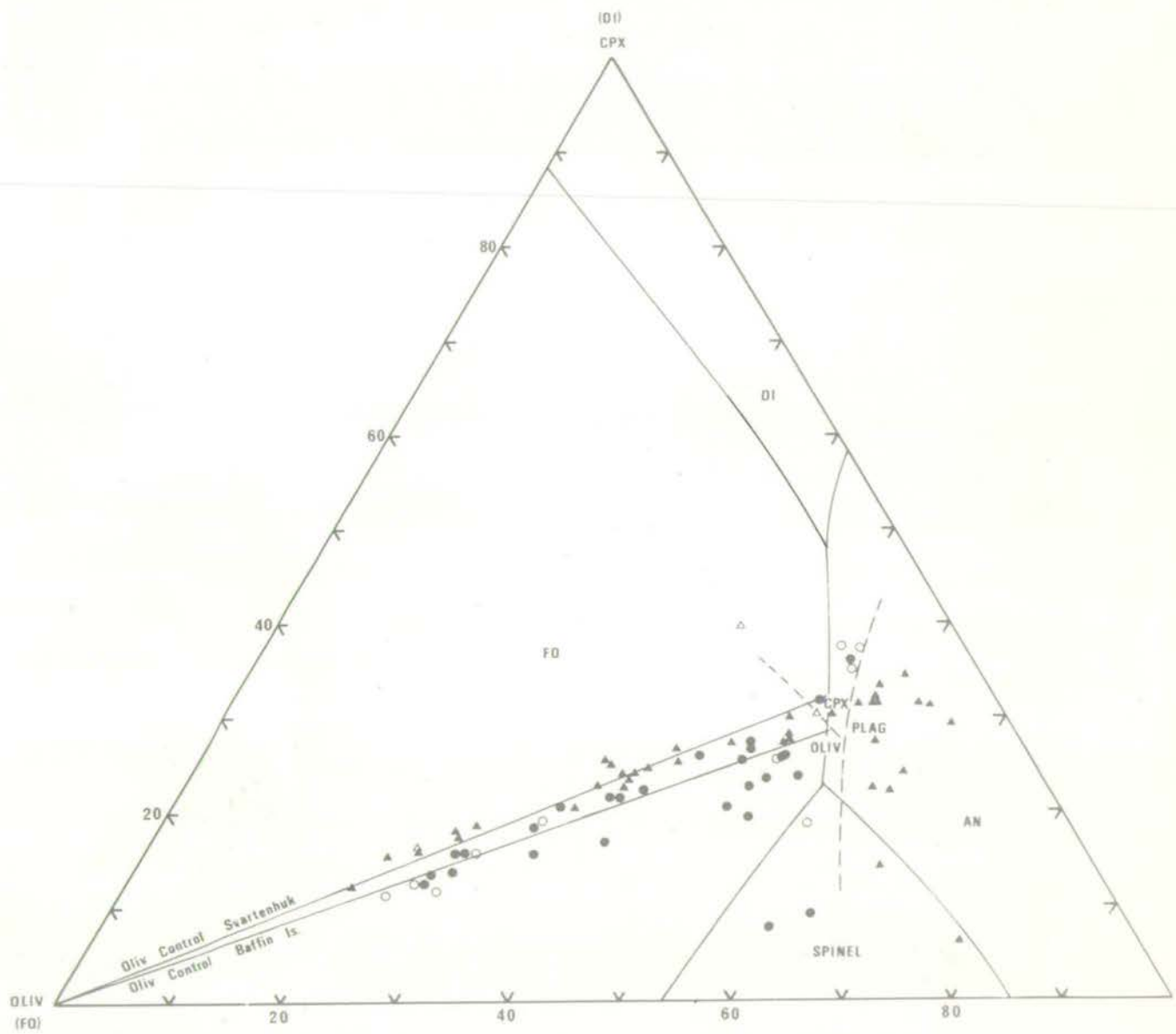


FIG. 24

of points about an olivine control line. This is, in fact, the case and in this projection there is no possible separation of the two suites. Also note the following:

- 1) all points project remote from the Qz corner
- 2) the position of the majority of points relative to the natural cotectic Oliv + Cpx + Flag + Liquid suggests appearance of Cpx as second phase after Oliv, contrary to the petrographically determined order of appearance of phases
- 3) those points projecting in the natural field of Oliv + Flag are some of the strong intra-flow differentiates of Baffin Island and feldspar-phyric basalts of Svartenhuk

B) Clinopyroxene Projection (Fig. 22)

When the projection point is a phase which, in the sequence of crystallization, appears third or later, the diagram may not yield useful information about the early stages of crystallization. Given this limitation, the following points should be noted:

- 1) no Sp + Cpx + Liquid field is encountered; the Sp primary phase volume enters the tetrahedron along the Fo-An join in Na- and Fe-free compositions but does not meet the Di volume and is rapidly suppressed by the addition of Na and Fe (Levin et al., 1964)
- 2) the synthetic invariant point Di + Fo + An + En + Liquid shifts towards Flag in the natural system, thereby extending the field of crystallization of olivine at the expense of plagioclase
- 3) the pseudo-univariant line drawn for natural rocks, which is the locus of liquid compositions in equilibrium with Cpx + Oliv + Flag, approximately

divides the predominantly olivine-phyric from the predominantly feldspar-phyric compositions

- 4) all compositions project close to the plane Oliv-Cpx-Plag, remote from the Qz apex and essentially on an olivine control line
- 5) most Baffin Bay basalts appear to project within the primary phase field of Cpx + Oliv except for the feldspar-phyric basalts of Svartenhuk, for some of which the first two phases may be Cpx + Plag; the feldspar-phyric basalts are discussed in detail in a later section
- 6) the end-members of intra-flow differentiation (open ornament) appear to have evolved along olivine control lines

C) Plagioclase Projection (Fig. 23)

This projection adds little to the previous two figures. Again it demonstrates that the field of Cpx crystallization from experimentally investigated natural basalts appears to be too large, as observed phase relations in the Baffin Bay basalts do not detect entry of Cpx phenocrysts as early as suggested by the natural cotectic Plag + Oliv + Cpx + Liquid. The widely scattered points in this projection include those feldspar-phyric basalts strongly enriched in plagioclase (the projecting phase) and two altered breccias from Baffin Island.

D) Quartz Projection (Fig. 24)

Because all points plot far from the Qz apex of the tetrahedron, comparison with the synthetic system Fo-Di-An (quartz-free base of the tetrahedron) should be meaningful. As usual, the partial phase diagram (natural system) is also shown, and, in addition, the following should be noted:

- 1) both suites of basalts plot on nearly identical, long and well-defined olivine control lines
- 2) enlargement of the field of Cpx at the combined expense of Oliv and Plag in the natural system again predicts appearance of Cpx as second phase in the Baffin Bay basalts, contrary to observed phase relations

In order to lend support to the hypothesis that olivine has been the phase principally responsible for the observed fractionation trends rather than some other phase or combination of phases, each sample has been recalculated in terms of the most picritic member in its province minus a calculated amount of olivine, using Fig. 24 as a basis. The calculation of the enrichment factor is simply the ratio of the distances from the olivine corner to the sample and the most picritic rock, and this is the factor by which all elements not involved in the composition of olivine are increased in the residual melt. For the incompatible elements there should be a one-to-one correspondence between the enrichment factor and weight per cent. (or ppm.) of these elements. This feature is shown in Figs. 25A, B, which demonstrate an approximate one-to-one correlation between minor elements and the enrichment factor for all olivine basalts in the two provinces. On the same diagrams it may be seen that the concentration of nickel simultaneously drops at a far greater rate than the rate of increase of the incompatibles, confirming that olivine and not some other, (Ni-poor), phase is precipitating.

E) Summary

In the foregoing projections it was demonstrated that the quaternary univariant loci of liquids in equilibrium with the projecting phase and two others in the relevant synthetic systems were not coincident with the natural, pseudo-quaternary univariant equilibrium curves. The differences in positioning

Fig. 25. Incompatible Elements vs. Enrichment Factor based on Olivine Removal.

A. Baffin Island basalts.

B. Svartenhuk basalts.

Symbols

x Ni

o Sr

■ Ga

▲ TiO_2

□ Zr

● Y

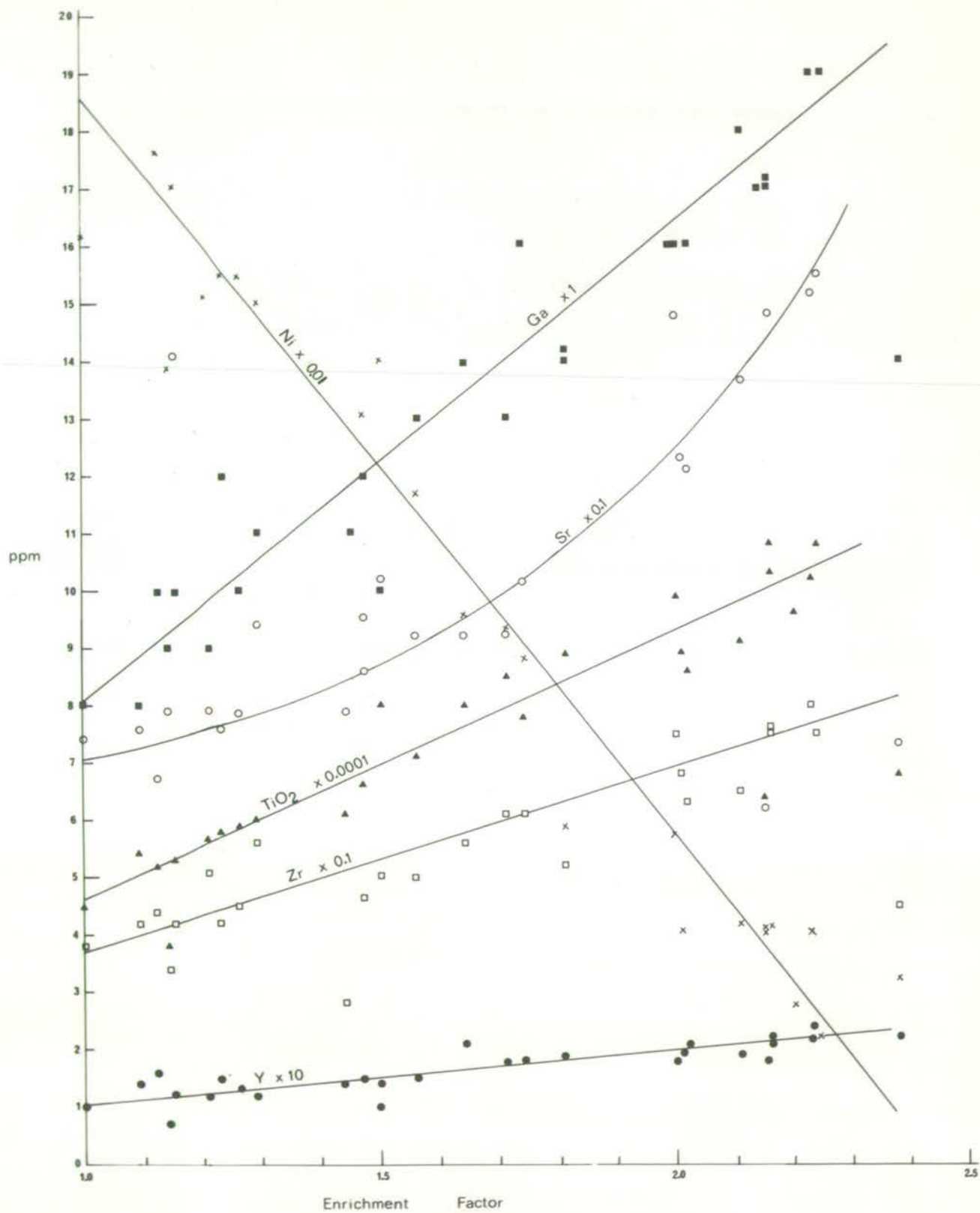


FIG. 25A

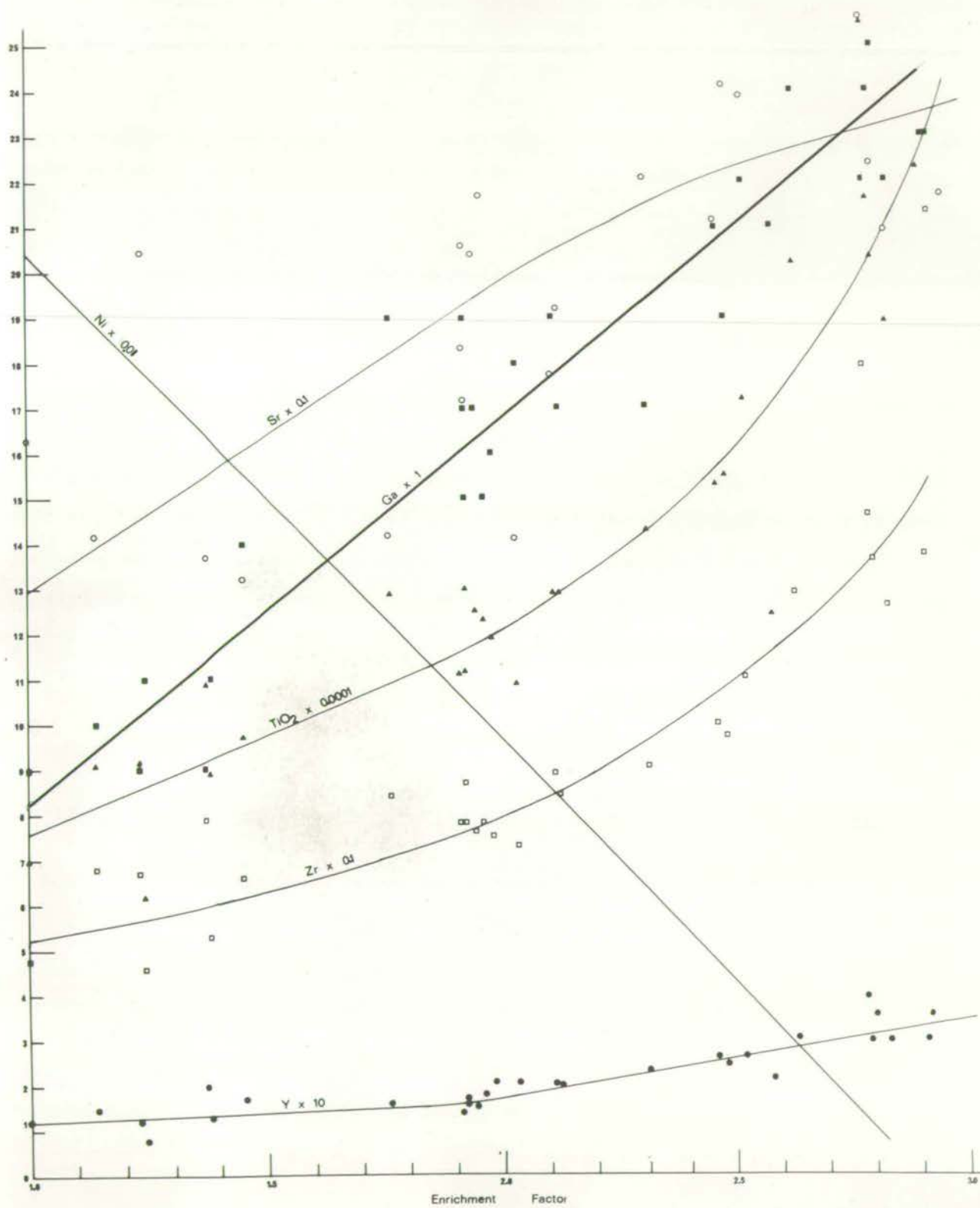


FIG. 25B

are caused principally by the introduction of Na and Fe into the natural system and this has the effect of expanding the primary phase volumes of the ferromagnesian against that of plagioclase.

In the olivine projection (Fig. 21) most of the points lie above the lower surface of the olivine primary phase volume, although some compositions are projected up onto this surface from a primary phase volume below. As most of the compositions in the olivine primary phase volume crystallize plagioclase as second phase it is proposed that a new pseudo-univariant line be drawn between the synthetic and natural cotectics. Predictions based on this new equilibrium curve would then agree with the observed phase relations.

In the clinopyroxene projection (Fig. 22) most, if not all, of the points lie below the primary phase volume of Cpx. The divariant surfaces between the Fo + An, and Oliv + Plag primary phase volumes are nearly vertical in this projection. Although it would have to be confirmed by melting experiments, more of the plagioclase-rich, olivine-poor intra-flow differentiates (open ornament) would be expected to crystallize plagioclase before olivine. Therefore, a new pseudo-univariant line on the lower surface of the clinopyroxene primary phase volume may be required between those already drawn for the synthetic and natural systems.

In the plagioclase projection (Fig. 23), the divariant surfaces again are nearly vertical and, as it stands, the natural pseudo-univariant line Plag + Oliv + Cpx + Liquid indicates a premature entry of clinopyroxene in these rocks. That is, some of the compositions between the natural and synthetic univariant lines might be expected to crystallize Plag + Oliv as the first two phases, especially the one normal Baffin Island basalt (FD-11) which has phenocrysts of olivine and plagioclase, and possibly one of the Svartenhuk compositions (664) which has only olivine phenocrysts.

In the quartz projection (Fig. 24) the phase relations predicted by the synthetic univariant equilibrium curves lying below the Baffin Bay basalt compositions are more nearly correct than those predicted by the natural pseudo-univariant curves lying above. The curves appropriate to the Baffin Bay basalts should lie somewhere between these two extremes.

In general, then, the satisfactory representation of observed crystallization in these basalts would require the drawing of loci of liquid compositions in pseudo-quaternary in-, mono- and di-variant equilibria which are intermediate between those obtained for the pure synthetic system Fo-Di-An-Qz , and those obtained from natural basalts which are not only Na- and Fe-bearing, but also enriched in K_2O and TiO_2 relative to the Baffin Bay basalts.

III. Theories Concerning the Nature of the Upper Mantle Composition and Derivative Partial Melts at High Pressure

A) Garnet Peridotite as a Likely Upper Mantle Composition

The attempt to sample the mantle directly (Project Mohole) having been abandoned, we must continue to rely on information from the various geophysical and geological disciplines for knowledge about the mantle. The data thus obtained serve to place stringent limits on the composition of the upper mantle and these are briefly reviewed here.

The P-wave velocities of 7.9-8.4 km./sec. obtained immediately beneath the M-discontinuity are matched only by those in dunites, eclogites and peridotites (Birch, 1952, 1961). Density considerations (Clark and Ringwood, 1964), the observed sharpness of the Moho boundary (Bullard and Griggs, 1961) and the failure of a basalt-eclogite transformation to account for both the continental and oceanic seismic discontinuity (Bullard and Griggs, 1961; Oxburgh, 1964; Cohen et al., 1967) argue strongly against eclogites occurring

in any great quantity immediately below the Moho. Earthquake foci apparently connected with volcanic activity suggest that basalt magmas are derived from the upper mantle. If this region were eclogitic, complete melting would be required to create a basaltic composition (Yoder and Tilley, 1962; O'Hara and Mercy, 1963; Cohen et al., 1967), and more eclogite nodules might reasonably be expected in the erupted lavas. Also Yoder and Tilley (1962) have shown that melting relations of eclogites, with clinopyroxene and garnet as nearly simultaneous liquidus phases, suggest that eclogite is the partial melting product of some other rock, e.g. garnet peridotite. However, O'Hara (1965) cautioned that eclogites probably do not represent the entire liquid formed by partial melting of a more primitive rock at high pressure but rather an accumulate from that liquid, since the temperature of beginning of melting of bimineralic eclogite is well above that of garnet peridotite (O'Hara, 1963a).

Heat flow measurements have shown that average values for continental and oceanic areas are practically equal, with a flux of $1.2 \text{ micro-cal./cm.}^2/\text{sec.}$ (Bullard and Griggs, 1961; Clark and Ringwood, 1964). Quite apart from the mantle inhomogeny that this implies regarding the radiogenic isotopes of K, U and Th, the significant point is that the observed heat flow is approximately equal to the value that would be expected if the earth had an over-all chondritic composition (Macdonald, 1959).

On the assumption that chondrites, representing the most abundant meteoric material, approximate undifferentiated average cosmic material, it has often been suggested that the earth also has a similar bulk composition (Urey, 1952). This theory receives considerable support from isotope geochemistry, which has shown that the stable isotope ratios of H, C, O, Si and S in chondritic meteorites and terrestrial ultramafic rocks are indistinguishable (Taylor, 1967). However, the chondritic model is not without opposition.

Total alkali contents and especially alkali ratios (Gast, 1965; Murthy^e and Stueber, 1967) would suggest an achondritic model to be more appropriate. Also, creation of the postulated iron core from an originally chondritic earth would leave the mantle with a residual composition close to that of orthopyroxene (O'Hara and Mercy, 1963), which is incompatible with the observed elastic properties of the upper mantle (Birch, 1952).

The consensus of opinion then, amongst geophysicists, is that the upper mantle is composed of mafic or ultramafic material. With eclogite ruled out on both geophysical and geological grounds, further petrological considerations will permit a more precise definition of the composition and mineralogy of the upper mantle.

Kimberlites, because of their association with diamonds and other high-pressure minerals, have long been regarded as derivatives of the upper mantle. O'Hara (1967) has shown from clinopyroxene compositions that ultramafic inclusions in kimberlite appear to have been drawn off the continental geothermal gradient at pressures of 30-45 kb. Also, Harris et al. (1967) did some statistical work on nodules in basalts and kimberlites and decided that the most probable mantle compositions were either pyroxene peridotite (i.e. up to 35% pyroxene) or garnet peridotite. Of all the ultramafic xenoliths that kimberlites bring to the surface, including garnet harzburgites, harzburgites, eclogites and lherzolites (Ito and Kennedy, 1968), the abundant garnet peridotite fragments alone could be regarded as undifferentiated mantle material capable of giving rise to basaltic liquids on partial melting. For this reason, such compositions as dunites, harzburgites and lherzolites are excluded. These more probably represent either residuals of partial melting of some other rock or crystal cumulates from a basic magma (O'Hara, 1968). Similarly, the strong association of peridotite nodules with alkali olivine basalts (O'Hara

and Mercy, 1963) suggests a genetic relation between these two compositions. These nodules could represent cognate accumulates from a liquid intermediate in composition between the peridotites and alkali olivine basalt, although this deduction has not gone unchallenged (Ernst, 1965; Davidson, 1967; Harris et al., 1967). On the basis of strong similarities in $Sr^{87}/^{86}$ ratios between basalts and the ultramafic inclusions in kimberlite, Stueber and Murthey (1966) decided that this evidence favours a garnet peridotite upper mantle.

Using a somewhat different approach, Ringwood (1962a, b; 1966a, b), Ringwood et al. (1964) and Green and Ringwood (1963, 1967) in a series of papers devised a scheme of matching a chondritic composition with a 3:1 mixture of dunite and basalt which they named pyrolite. They have shown that this composition is characterized by several mineral assemblages under varying P-T conditions, including plagioclase, spinel and garnet peridotite. They concluded that mineralogical zoning consequently may exist in the mantle, thereby providing an explanation for the layering inferred from seismic studies.

In short, garnet peridotite meets the requirements of geophysical and petrological considerations and will be treated in further discussions as the currently most acceptable mantle composition. What remains to be discussed, at this stage, is the behaviour of such a composition under conditions of partial melting at high pressure.

B) Partial Melting Product of Garnet Peridotite at High Pressure

Bowen (1928) stated that "large amounts of olivine never occur in solution in magmatic liquids", large amounts being defined as greater than 12-15%. However, Bowen added the qualification that large amounts of olivine may have been in solution "at an earlier time" and, although the prevailing

conditions of that time were not specified, Bowen almost certainly meant that the olivine was of cumulative origin and "was never in solution in the liquid now represented by the groundmass". This idea prevailed for nearly twenty-five years, after which it began to be challenged by Drever (1952), who examined the evidence both for and against gravitative accumulation of olivine. Later Drever (1956) and Drever and Johnston (1957) decided that the delicate skeletal olivines in certain of their picritic compositions from Ubekendt Island, west Greenland, could not be explained other than by crystallization in situ. They cited some experimental work on quenched picritic compositions which developed olivine habits similar to those in the Ubekendt material, and in the light of this work they called for a raising of the olivine solubility in a basaltic magma to 25%. Nevertheless, they did not suggest that there might be any special pressure-temperature conditions required for this increased solubility.

In a series of papers (O'Hara and Mercy, 1963; O'Hara and Yoder, 1963, 1967; O'Hara, 1963b, 1965, 1968), O'Hara has pioneered the attempt to define the composition of the first and successive liquids produced during partial melting of garnet peridotite at mantle pressures. From an early date it was pointed out that the liquid generated at depth need not necessarily have compositions like basalts of high crustal levels; i.e. the whole concept of basalt as a "primary" magma was being challenged. At the same time, it was clear that this high-pressure liquid must have a reaction relationship with orthopyroxene and also be able to lose olivine if biminerallitic eclogites were ever to be formed as cumulates from that liquid at elevated pressures. O'Hara and Yoder (1963) and O'Hara (1963b) suggested that the partial melting product of 4-phase peridotite (i.e. olivine + 2 pyroxenes + alumina-rich phase) should be either a hypersthene- or a nepheline-normative picrite in

composition. They argued from the phase relations that the liquid on partial melting would have to be SiO_2 -poor relative to the hypersthene eclogite thermal barrier (Fig. 26A), and since garnet was likely to be a major phase entering the first liquid, the CIPW norm of that liquid was expected to contain both olivine and hypersthene. O'Hara (1965) cautioned that only rarely would this picritic liquid be brought to the surface unmodified. Further refinement led O'Hara and Yoder (1967) to state unequivocally that "the partial melting product of garnet-lherzolite at 30 kilobars has the composition of a hypersthene-normative picrite basalt". Ito and Kennedy (1967) arrived at the same conclusion regarding the partial melting product of their peridotite (KA64-16) at 40 kb. and confirmed qualitatively, at least, the decidedly picritic nature of the early liquid. Because of the difficulty of quenching the small amounts of liquid produced, no workers so far have obtained a direct chemical analysis to confirm the inferences concerning the normative affinities of the early-formed liquids.

In the synthetic system, Davis (1964) and Davis and Schairer (1965) discovered that the partial melt of a composition in the plane Fo-Di-Py at 40 kb. produced a liquid with a normative composition approximating $\text{An}_{32}\text{Di}_{22}\text{En}_{26}\text{Fo}_{20}$, i.e. a hypersthene-normative picrite.

IV. "CMAS" Projections

While the simple normative basalt tetrahedron of Yoder and Tilley (1962) provides an adequate framework for studying phase relations at 1 atmosphere, its usefulness in unravelling the petrogenetic knot is limited. It is the phase relations, at likely mantle pressures, which need investigation in order to ascertain the composition of partial melts produced at depth, as well as possible fractionation schemes under isobaric and polybaric conditions, i.e.

Fig. 26. A. Part of the CMAS tetrahedron to illustrate that the partial melting product of garnet peridotite at high pressures may be a hypersthene-normative picrite.

The stippled plane En-Di-Py is coincident with the plane of natural bimineralic eclogites, $\text{Cpx}_{ss}\text{-Gnt}_{ss}$, and is a thermal barrier at 30 kb. Therefore, olivine- or quartz-bearing eclogites will begin to melt at temperatures lower than those for bimineralic eclogites. All compositions on the Di-Py join are olivine normative; therefore, the liquid produced by partial melting of olivine-rich hypersthene eclogite (garnet peridotite) must be undersaturated relative to the high pressure divide and thus be picritic.

The normative character of the liquid depends on the proportions in which garnet (high normative hypersthene) and clinopyroxene (normative nepheline) enter the first liquid. The position of the first liquid in the melting of bimineralic eclogite at 30 kb, relative to the Di-Py join is such that the liquid will be hypersthene normative. Since Cpx and Gnt are the principal phases entering the first liquid in the melting of garnet peridotite, and assuming they do so in approximately the same proportions as in the melting of bimineralic eclogites, the high pressure partial melt of garnet peridotite will be a hypersthene-normative picrite.

B. Enstatite (MS) Projection onto $\text{C}_2\text{S}_3\text{-M}_2\text{S-A}_2\text{S}_3$ (Fig. 27).

Olivine (M_2S) Projection onto CS-MS-A (Fig. 28A).

Olivine (M_2S) Projection onto C-MS-A (Fig. 28B).

Diopside (CMS_2) Projection onto $\text{C}_3\text{A-M-S}$ (Fig. 29).

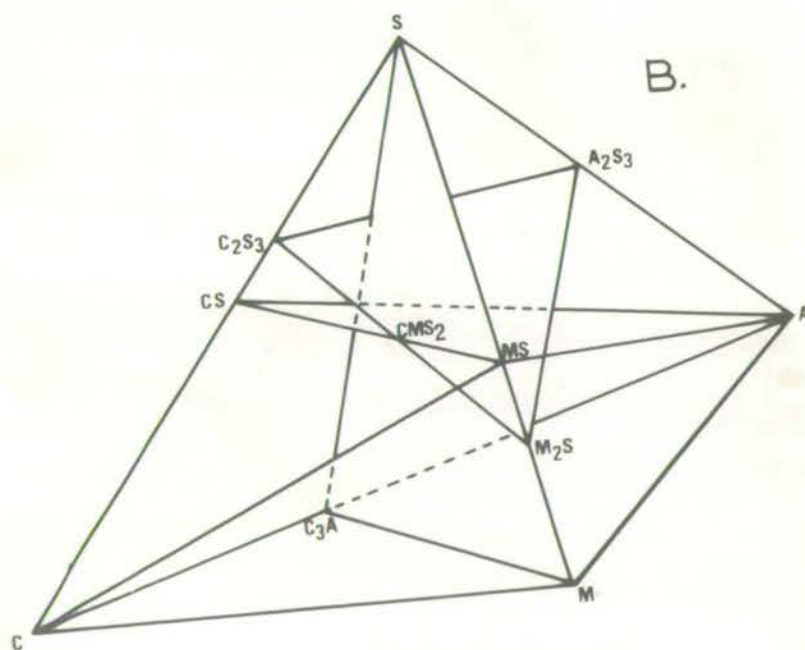
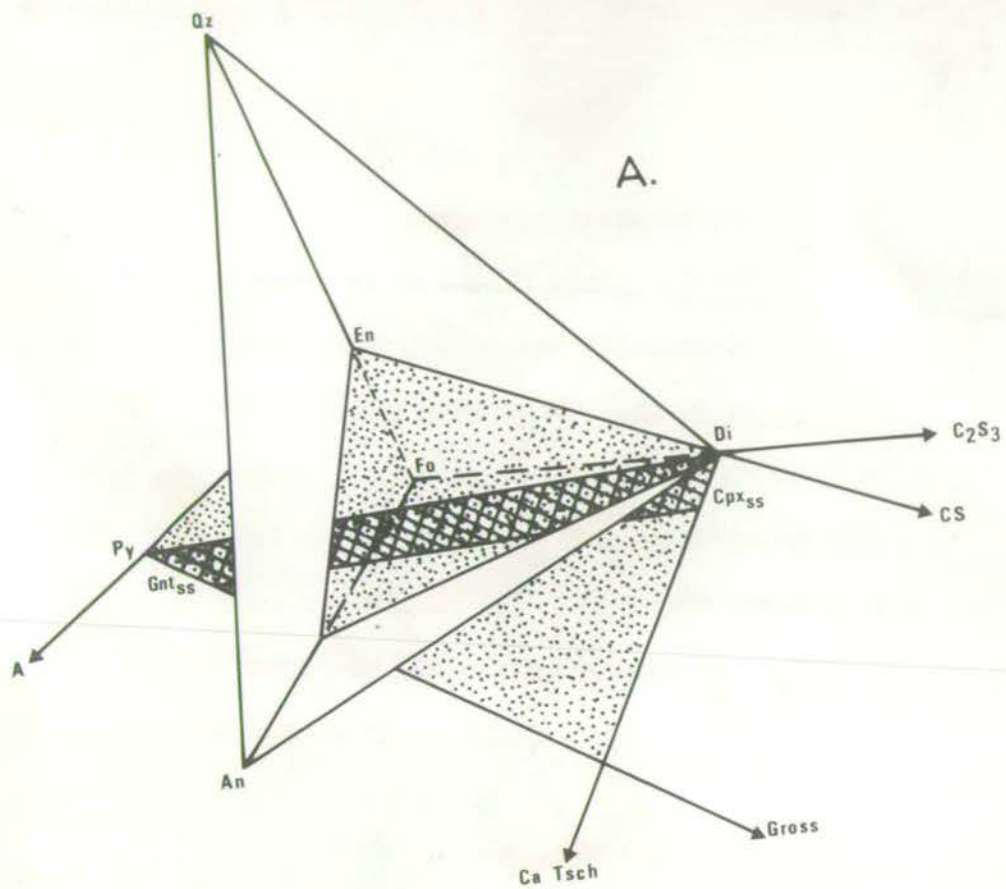


FIG. 26

Fig. 27. CMAS Tetrahedron, Enstatite (MS) Projection onto $C_2S_3-M_2S-A_2S_3$.

Compositions lie on a strong olivine control line which may be subdivided into three segments along its length.

Group I Cumulates.

Group II Possible primary compositions.

Group III Evolved compositions.

Fig. 28. A. CMAS Tetrahedron, Olivine (M_2S) Projection onto $CS-MS-A$.

B. CMAS Tetrahedron, Olivine (M_2S) Projection onto $C-MS-A$.

Fig. 29. CMAS Tetrahedron, Diopside (MS_2) Projection onto C_3A-M-S .

Ornamentation for these figures as in Fig. 7.

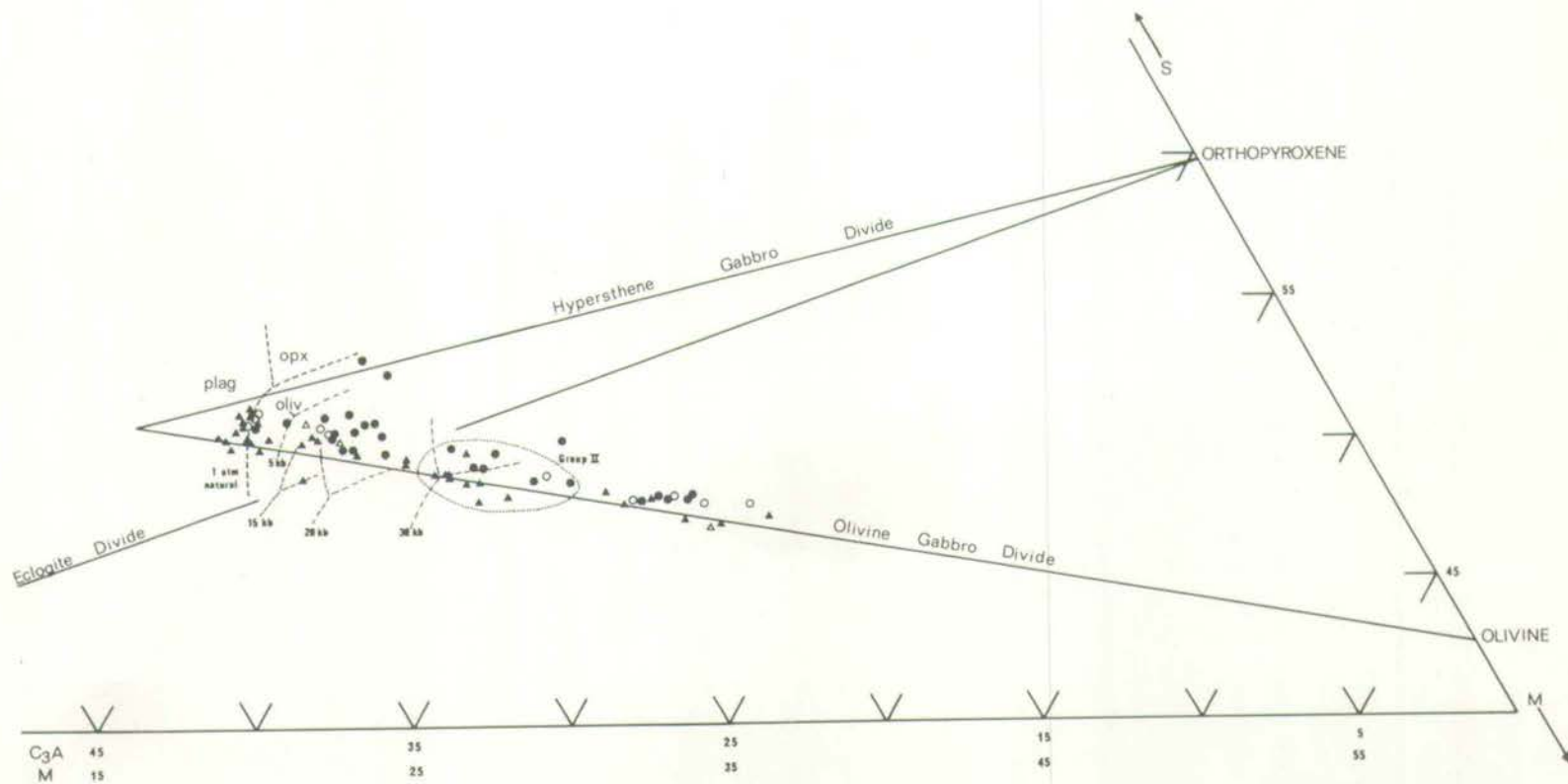


FIG. 29

to ascertain the complete history of the liquid.

The method for reducing the multicomponent analyses into the 4-component "CMAS" has been described by O'Hara (1968). Fig. 26B shows the positions of the four planes of projection used in the following discussion.

A) Projection 1: Enstatite (MS) onto $C_2S_3-M_2S_3-A_2S_3$ (Fig. 27)

As expected, the variation within the two suites lies along a well-defined olivine control line up to the point where the feldspar-phyric basalts predominate. There is also the considerable degree of overlap that was noted in previous variation diagrams. Both suites show a roughly trimodal distribution in that they can be divided into three groups along the length of the olivine control line. An explanation of this feature, involving a continuous path of fractionation upon which has been superimposed discontinuous eruption of material, is adopted here. The three groups are now discussed in detail:

Group I The points in this group are either olivine-enriched bases of thick flows (mainly on the Baffin Island side) or recognizably cumulitic flows (mainly on the Greenland side), characterized by large olivine phenocrysts as opposed to the more common microphenocrysts. Therefore, at least some, and perhaps all, of the points in this grouping may be regarded as high-level cumulates and are thus not particularly relevant to any discussion of derivation of the entire suite of rocks from the mantle.

Group II At least in Svartenhuk this group of points consists of a petrographically and stratigraphically distinct suite of lavas, characterized by olivine microphenocrysts (or skeletal olivines) and everywhere occurring at the base of the volcanic pile, i.e. the first eruptives. The stratigraphic distinction is not as clear on Baffin Island, but

petrographically they are also characterized by a profusion of olivine microphenocrysts and show no tendency towards olivine cumulus enrichment.

Group III This group consists of the leucocratic segregation veins in thick flows (mainly on Baffin Island), olivine-poor basalts from both areas and the feldspar-phyric basalts (Svartenhuk only). This grouping is also of small importance when consideration of the partial melting of the mantle is involved, because both petrographic and chemical evidence suggest that these are the products of low-pressure fractionation.

The pressure-dependent positions of the pseudo-invariant point in the natural system (O'Hara, 1968) are also plotted on this projection. This pseudo-invariant point is described by the equilibrium Oliv + Opx + Cpx + Al-Rich Phase + Liquid, where the aluminous phase may be plagioclase, spinel or garnet, depending on the pressure. In addition, partial cotectics for some 4-phase equilibria are shown. Note that with increasing pressure the composition of the pseudo-invariant point becomes increasingly picritic.

At a pressure of approximately 30 kb., the points in Group II (i.e. those being neither olivine cumulates nor late-stage liquids) roughly coincide in projection with the position of the pseudo-invariant point. Therefore, not only can these compositions be parental to Groups I and III at low pressure through addition and removal of olivine, but also they may represent a primary liquid (the unmodified partial melt of the mantle) at 30 kb. The concentrations of incompatible elements in these rocks are primitive relative to other tholeiites, thus supporting the idea that they may be primary liquids. These Group II compositions (samples C-25b, DX-24 and 31, I-64 and 102, P-5, R-13,

S-28, 539, 544, 548, 592, 648, 651, 655 and 658) will be used in the subsequent discussions of petrogenetic models.

B) Projection 2: Olivine (M_2S) onto CS-MS-A (Fig. 28A)

By analogy with the olivine projection in the simple basalt tetrahedron (Fig. 21), the view along an olivine control line in this projection should show a strong clustering of points. In fact, what emerges is a short, but well-defined, trend back towards the MS corner. Four possibilities may be considered by way of explanation:

- 1) The trend might reflect a period of earlier (say, intermediate pressure) fractionation of orthopyroxene (Green and Ringwood, 1964), i.e. a "fossil trend" or proliferation line (Cox, 1967). However, there is no corroborative petrographic evidence such as large xenocrysts or partially resorbed phenocrysts of orthopyroxene (Jamieson, 1966).
- 2) The trend might reflect an increasing degree of partial melting in the mantle, during which increasing amounts of the orthopyroxene (MS) molecule are entering the liquid in the equilibrium harzburgite + liquid, i.e. under conditions of advanced partial melting. If this mechanism is the cause of the trend, then the positions of the loci of liquids in equilibrium with olivine and the three other phases taken in pairs indicate that mantle melting must have been taking place in the pressure range 10-20 kb. Also, it should be demonstrable that rough indices of primitiveness such as the levels of K_2O or P_2O_5 would behave in a linear fashion along the trend, which, in fact, they do not.
- 3) Errors in the determination of Na_2O will produce a shift of the points directly along what would appear to be an orthopyroxene control line in Fig. 28A. The degree of shift may be stated as being approximately 25%

apparent removal of En per 1% absolute of Na_2O error. Flame photometric analysis of soda is better than $\pm 2\%$ of the amount present, therefore representing at worst 0.5% apparent removal of En. On the scale of these diagrams this error could not be detected.

- 4) The trend could be merely a projection effect resulting from the geometry and therefore have no petrogenetic significance. The line of sight from olivine through the points in the body of the tetrahedron intersects the projection plane CS-MS-A at a very oblique angle. This will cause a three-dimensional cylinder of points along an olivine control line to plot as an ellipse on the projection plane, with the long axis of the ellipse lying in the same plane as the control line and apparently back towards the MS corner. This is in fact what is observed, and a qualitative confirmation is available in Projection 3 (Fig. 28B) discussed below.

Even with the trend ignored, the positions of the 1 atmosphere cotectics do not agree with the petrographically determined order of crystallization. As in the simple normative basalt tetrahedron, a set of cotectics intermediate in position between the natural and synthetic curves best describes the crystallization history of most of the rocks, i.e. olivine, plagioclase and clinopyroxene in order of appearance.

C) Projection 3: Olivine (M_2S) onto C-MS-A (Fig. 28B)

This projection is of the same type as Projection 2 except that in this case the line joining Olivine to the group of points in the tetrahedron is now more nearly perpendicular to the plane of projection, C-MS-A. Note that the apparent trend produced in this case back towards MS is considerably shortened relative to the same trend in Projection 2. It should now be clear that there are no petrogenetically significant trends in the Olivine projections,

and therefore in future discussions involving this type of projection (Figs. 30, 32, 33) the apparent trend will be reduced to a circle of radius equal to the semi-minor axis of the ellipse of Group II points in Fig. 28A, and centred at the intersection of the minor and major axes of the ellipse.

D) Projection 4: Diopside (CMS_2) onto $\text{C}_3\text{A-M-S}$ (Fig. 29)

The discussion of this projection is essentially the same as that for the preceding MS projection. The trimodal distribution along the olivine control line is preserved when seen from Diopside. Again, some of the pressure-dependent cotectics are shown. The area of overlap between the Baffin Island and Svartenhuk Group II rocks will be used in future discussions as the most likely composition of the parental liquid in these two geographical localities.

V. Three Petrogenetic Models

Before actually considering the models of magma generation, it is useful to list certain limitations and requirements to which adherence must be paid in any consideration of petrogenesis. A model which does not satisfy the following conditions should be rejected:

- 1) Assuming current estimates (Engel, Engel and Havens, 1965; Ringwood, 1966a; Gast, 1968; O'Hara, 1968) of the mantle composition are reasonable with respect to the incompatible elements, there must be a high degree of partial melting of garnet peridotite to account for their low concentration in the liquid.
- 2) Allied to the first consideration is the requirement that the liquid, once formed at depth, must be subjected to a minimum of crystal fractionation (a process which would tend to raise the level of the incompatible elements).

However, conditions should exist to allow a small degree of eclogite fractionation to operate on the primary liquid as a means of producing the Svartenhuk parental magma.

- 3) Ultramafic xenoliths are nowhere present in the field; therefore, if they appear in the magma at any stage, whether as original mantle, residual mantle or cognate accumulates, they must be totally lost by sinking.
- 4) The pronounced settling of olivine crystals in thick lava flows indicates that the magma was sufficiently fluid to permit crystal-liquid fractionation. Therefore, in order to bring the olivines to the surface, the magma must have risen rapidly in the condition of liquid + crystals. Either that, or else if all the skeletal olivines in the one-phenocryst basalts of Group II are regarded as quench products, then the magma must have risen even more quickly in a superheated condition. These considerations, plus the non-attainment of equilibrium by these compositions in the 1 atmosphere invariant condition, require a rapid rate of ascent of the magma in any proposed model.

Three models are now considered for the generation of magmas in the mantle with compositions equivalent to the Group II basalts of Figs. 27, 29. The second of these involves partial melting at a pressure of 30 kb. and is preferred over the other cases at 20 kb. and 40 kb. because of its general agreement with the above criteria and relative simplicity.

A) Partial Melting at 20 Kilobars (Fig. 30)

From work done in the simple normative basalt tetrahedron, it was demonstrated that there was often a discrepancy between the positions of the cotectics drawn for synthetic compositions and those for natural rocks. It

was also found in Fig. 28A that a set of cotectics about half way between the 1 atmosphere natural and synthetic cotectics best agreed with the petrographic evidence concerning the order of appearance of phases. This difference in position of the univariant equilibria continues to high pressures, and for this reason new sets of equilibrium curves applicable to Baffin Bay rocks have been drawn between the natural and synthetic curves in each of the three projections of Fig. 30.

In the olivine projection the compromise curves were drawn between the 20 kb. naturals (O'Hara, 1968) and the 20 kb. synthetics (Kushiro, 1968). There is insufficient data in the diopside projection to permit evaluation of either the amount or the sense of shift of the cotectics; therefore, those derived from phase relations in natural rocks have been left unaltered as a first approximation. Information available from work at 30 kb. suggests only a slight shift of the invariant point away from the En corner in the synthetic system relative to the natural. Therefore, the 20 kb. natural pseudo-invariant point, Oliv + Opx + Cpx + Al-Rich Phase + Liquid, has been adjusted by an amount equal to one-half the separation measured between natural and synthetic cotectics at 30 kb.

The composite projection (Fig. 30), which involves only the Group II compositions of Figs. 27, 29, suggests that starting with a mantle of spinel peridotite possibly poorer in Al_2O_3 and richer in olivine than average garnet peridotite (Ito and Kennedy, 1967), the partial melting history would be as follows:

Oliv + Opx + Cpx + Sp	(subsolidus)
Oliv + Opx + Cpx + Sp + Liquid	(first liquid; isobaric pseudo-invariant condition)

Oliv + Opx + Cpx + Liquid	(Sp out; residual lherzolite + liquid)
Oliv + Opx + Liquid	(Cpx out; residual harzburgite + liquid)

If the Group II compositions of Baffin Bay are to be regarded as former liquids at 20 kb. which were subsequently rushed to the surface unmodified, then it is evident from Fig. 30 that this liquid was in equilibrium with a harzburgitic mantle just prior to eruption. This implies a high degree of partial melting and is thus entirely consistent with the low levels of incompatible elements which these rocks display. The relationship between temperature, degree of partial melting and enrichment factor of the incompatible elements is given in Fig. 31 (after O'Hara, 1968).

In further support of the 20 kb. case, it should be added that earthquake foci associated with current oceanic ridge structures, which may coincide with the region of magma production, occur at depths of less than 70 km. The oceanic analogy is further strengthened by the degree of similarity of certain trace elements in these rocks with those dredged off the sea floor (Tables 8, 9). However, the model advanced in Fig. 6 was one of rifting of the continental crust, and certainly the lavas as exposed today do belong to the continental environment, beneath which a spinel-bearing mantle is not believed to exist (Ito and Kennedy, 1967). A possible solution to this problem may be to suppose that the rifting apart of Baffin Bay was the mechanism by which garnet peridotite was initially converted to spinel peridotite by pressure release and finally partially melted on a further reduction of pressure. Green and Ringwood (1967) are not averse to appealing to "adiabatic rising diapirs" of mantle material in order to effect partial melting, and Oxburgh and Turcotte (1968) have concurred.

The initial partial melt of peridotite at 20 kb. is nepheline normative, but in advanced partial melting the liquid moves back into the hypersthene

Fig. 30. Model for Partial Melting at 20 kb.

A. Olivine Projection, cf. Fig. 28A.

B. Diopside Projection, cf. Fig. 29.

C. Orthopyroxene Projection, cf. Fig. 27.

Black area denotes field of primary, Group II, compositions.

agp = average garnet peridotite (Ito and Kennedy, 1967).

Cotectic lines are those appropriate to the Group II compositions
at 20 kb.

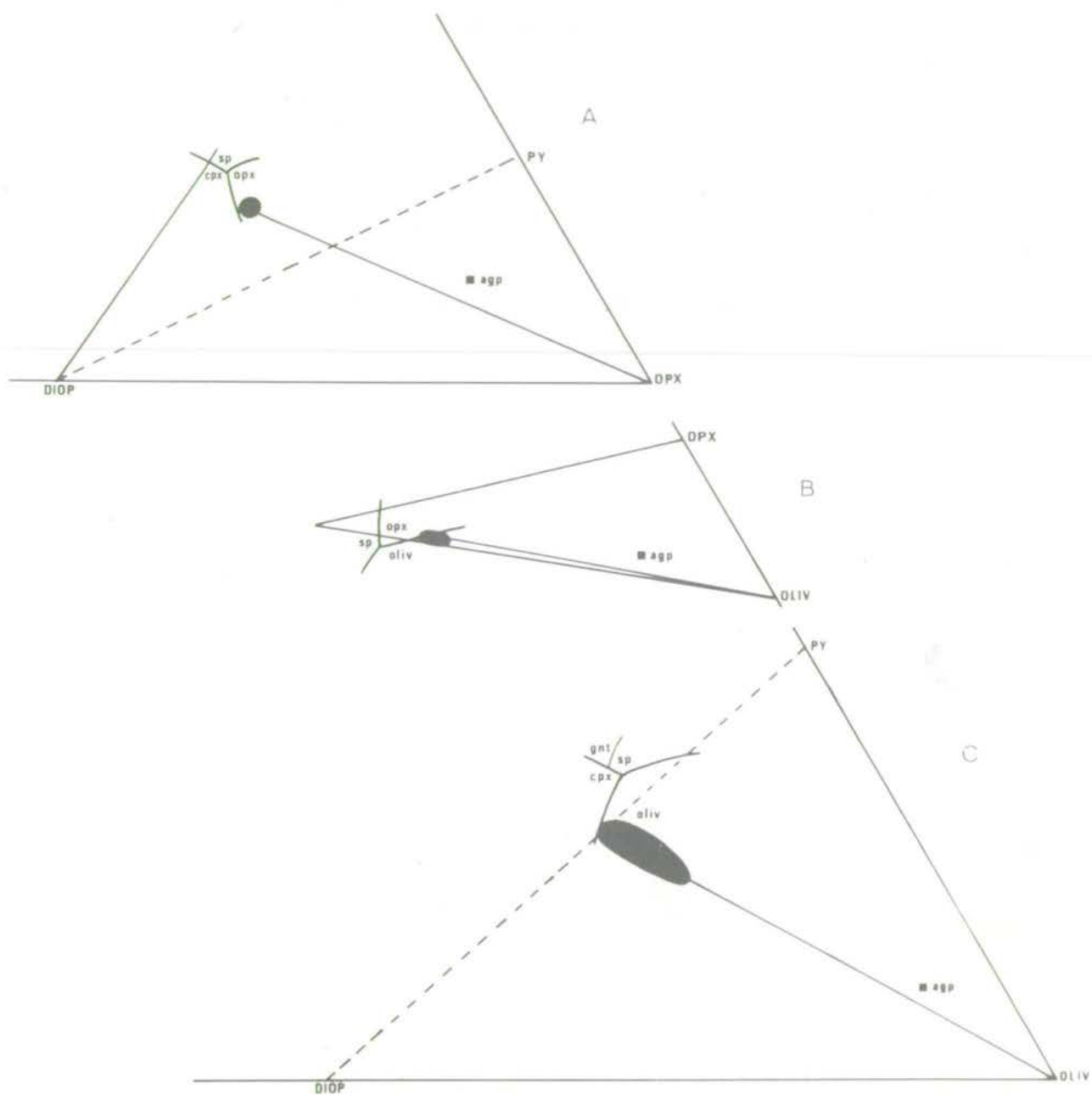


FIG. 30

Fig. 31. Behaviour of Incompatible Elements on Partial Melting (after O'Hara, 1968).

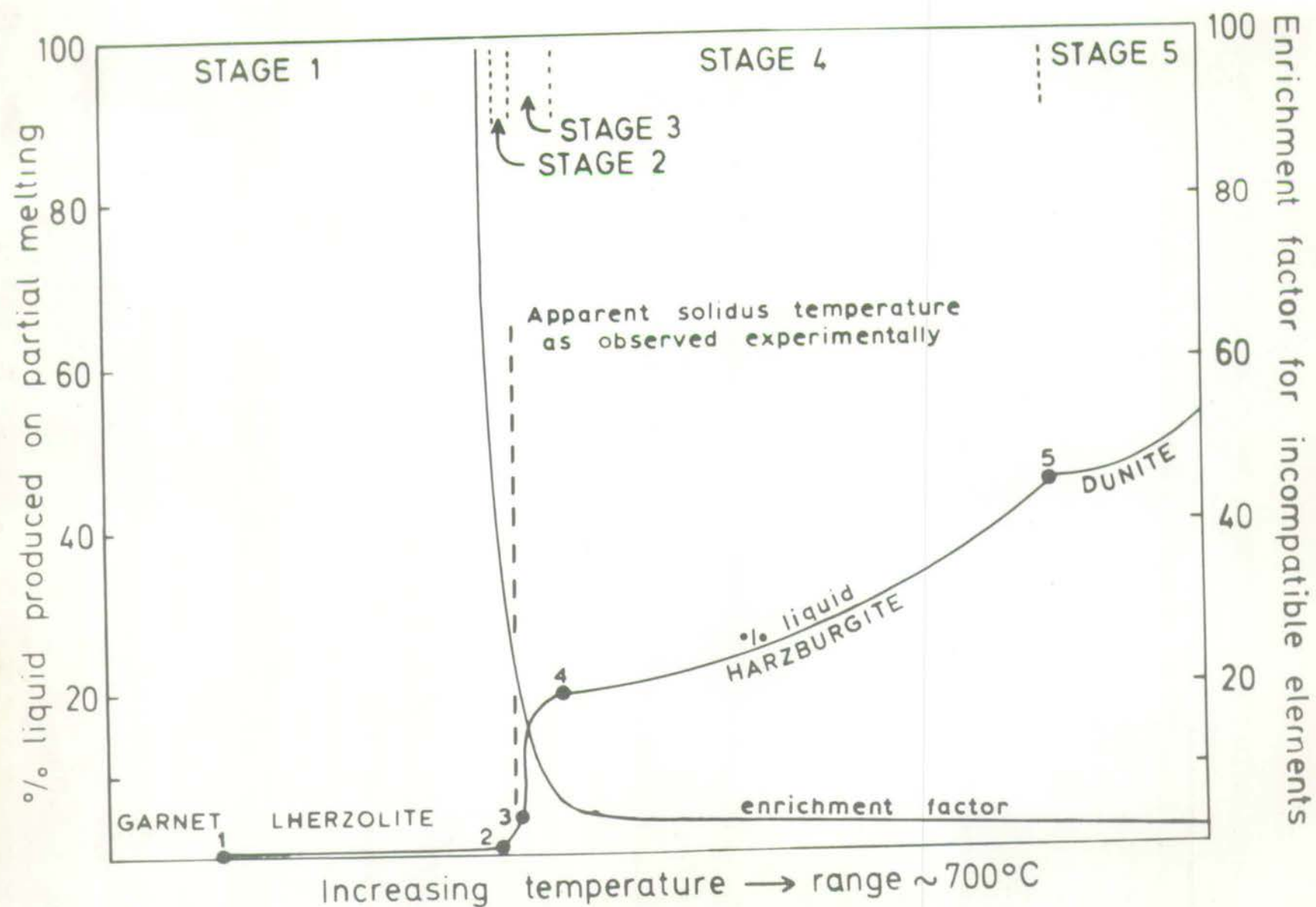


FIG. 31

Fig. 32. Model for Partial Melting at 30 kb. (cf. Fig. 30).

Fig. 33. Model for Partial Melting at 40 kb. (cf. Fig. 30).

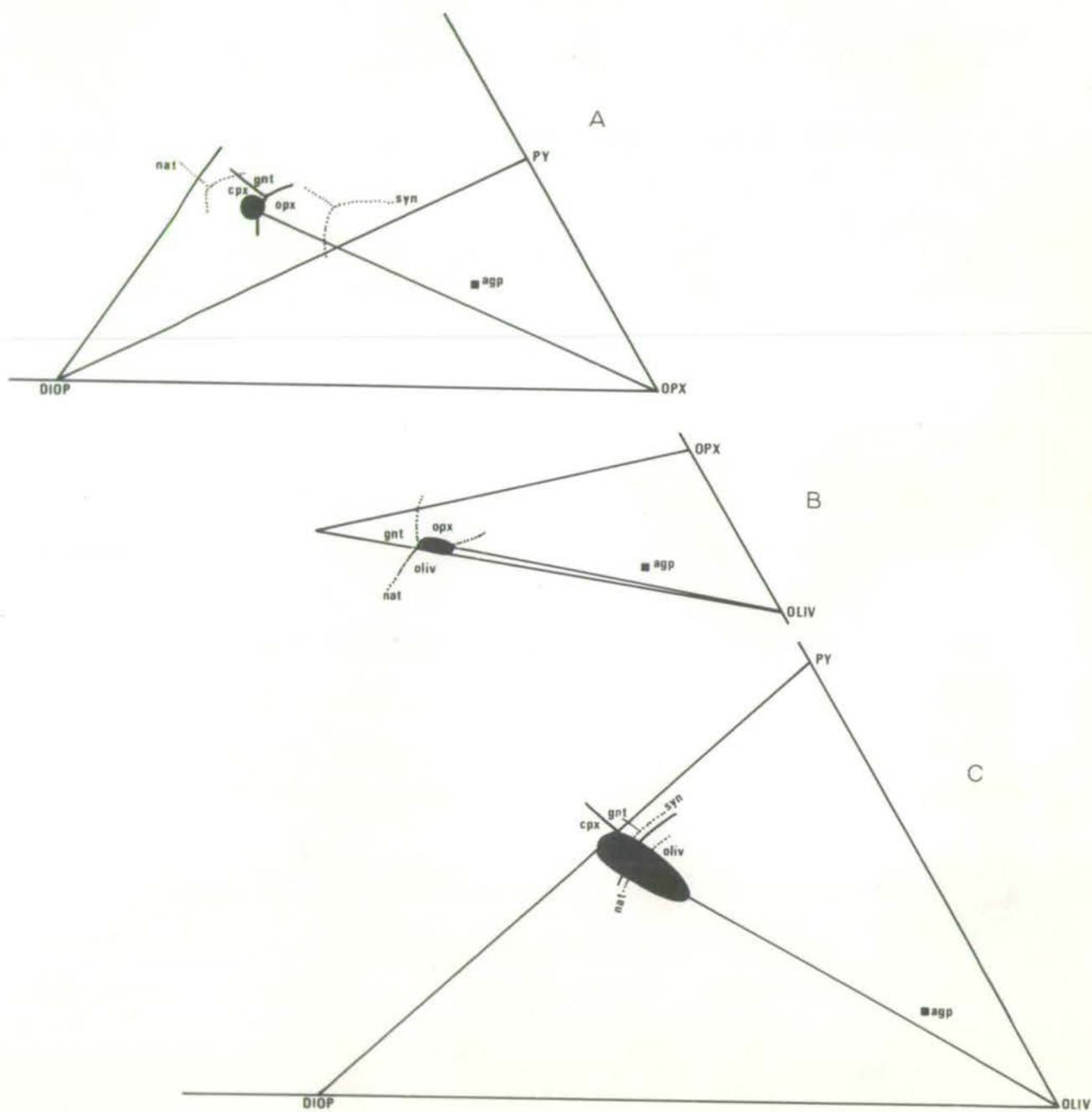


FIG. 32

normative volume. A high degree of partial melting has already been demonstrated, and thus far the 20 kb. model satisfies the first of the four conditions which preceded this section.

The initial objection to this model is that it has been necessary to assume that the mantle composition should have a bulk chemical composition different from average garnet peridotite and yet still contain spinel as a stable subsolidus phase. The composition of the necessary mantle peridotite can be stated with no more precision than that it must lie on a control plane through Oliv, Opx and Liquid during advanced partial melting. The other objection is that it is only after the liquid has passed through the pseudo-invariant point by losing both its olivine and orthopyroxene in reaction relationships that eclogite fractionation can begin. The position of the Group II compositions relative to the pseudo-invariant point is so disposed as to make impossible any opportunity for eclogite fractionation, even if it were possible at this pressure, which seems unlikely as garnet is not the stable alumina-rich phase.

B) Partial Melting at 30 Kilobars (Fig. 32)

In the olivine projection the positioning of the synthetic cotectics was achieved by projecting compositions studied by O'Hara and Yoder (1967, Table 1) into the plane CS-MS-A. From the experimentally determined appearance of phases it was possible to fit a consistent set of cotectics to these projected compositions. The natural cotectics are from O'Hara (1968), and the compromise cotectics for the Baffin Bay basalts are taken half way between these and the synthetic ones. As in the case of the 20 kb. partial melting, sufficient data are not available for the precise positioning of the pseudo-invariant point or cotectic lines in the diopside projection.

Examination of the olivine and orthopyroxene projections suggests that there may be a small net shift of the pseudo-invariant point towards the Opx corner. If this is the case, then the position of the natural cotectics in the diopside projection of Fig. 32 closely approximates the position of the synthetic cotectics and those applicable to the Baffin Bay basalts. In the enstatite projection the synthetic cotectics were drawn to conform with phase relations studied by O'Hara and Yoder (1967), and the natural cotectics are from O'Hara (1968). The compromise cotectics for Baffin Bay rocks are drawn in an intermediate position between the natural and synthetic curves.

The individual parts of the composite projection indicate that the projected positions of the Group II compositions agree fairly closely with the position of the pseudo-invariant point. The history of partial melting would be as follows:

Oliv + Opx + Cpx + Gnt	(subsolidus)
Oliv + Opx + Cpx + Gnt + Liquid	(first liquid; pseudo-invariant condition)
Oliv + Opx + Liquid	(Cpx and Gnt out simultaneously; residual harzburgite + liquid)

The same problem regarding the composition of the mantle peridotite exists here as existed in the 20 kb. case. The peridotite bulk composition must lie on a control plane through Oliv, Opx and Liquid during advanced stages of partial melting.

The positions of the Group II compositions relative to the pseudo-invariant point indicate that partial melting probably would not have advanced very far into the harzburgite + liquid equilibrium. The immediate consequence of this fact is that the degree of partial melting would appear to be less than in the scheme of partial melting at 20 kb. If the degree of partial

melting is less in the present case, then at least part of the deficiency of some trace elements in these basalts would have to be attributed to original depletion in the mantle material which was being processed. However, the degree of partial melting in the two cases, 20 kb. and 30 kb. regimes, is probably closer than Fig. 31 would suggest. This occurs simply because the larger olivine component of the liquid at any stage in the 30 kb. case means a larger ratio of liquid to residual mantle than at comparable temperatures above the beginning of melting in the 20 kb. case. Therefore, with the 30 kb. case also reaching the harzburgite + liquid equilibrium, the relative proportion of liquid may even be greater than in the previous case.

The most favourable argument for the 30 kb. case is that it allows both the desired degree of partial melting to take place and the required conditions for eclogite fractionation to prevail. Before any crystallization took place, part of the magma may be imagined to have escaped to the surface, and it is now represented by the Baffin Island lavas. The remainder of the liquid was uniquely situated relative to the pseudo-invariant point (as nearly as the position of that point can be estimated), so that an initial small amount of fractionation of harzburgite at depth would quickly lead to the conditions for eclogite fractionation. Once such fractionation had begun, the bulk chemical composition of the liquid would not change greatly, although substantial enrichment of the incompatible elements in the potential Svartenhuk magma, as indicated by Table 3, would take place. That evolved magma would then be required to erupt from about 100 km. quickly enough to permit retention of any new phenocrysts formed as the olivine primary phase volume expanded on pressure release to envelop the liquid composition, but slowly enough to allow complete loss of the small amounts of cognate harzburgitic and eclogitic cumulates. Therefore, the Baffin Island parental magma may be a true primary

liquid, whereas a portion of that primary liquid which suffered fractionation at high pressure later became the Svartenhuk parental magma.

C) Partial Melting at 40 Kilobars (Fig. 33)

Since data on natural rocks are not available at this pressure, the position of the cotectics in the olivine projection is a compromise between an estimated natural position and the determined position in the synthetic system (Davis, 1964; Davis and Schairer, 1965). Even less information is available for the diopside projection; so the 30 kb. natural and an estimated 40 kb. set of equilibrium curves are shown. In the enstatite projections there has so far been little difference between the projected positions of the natural and synthetic invariant points, and so the unmodified 40 kb. synthetic curves of Davis and Schairer (1965) have been used.

Regardless of the mantle composition, the positions of the Group II points, representing erupted, near-liquid compositions, indicate that partial melting at 40 kb. must have produced liquids at least as basic as those points marked by open circles. Up to that point this scheme of partial melting does not preclude consideration of the mantle as average garnet peridotite. In this case, the partial melting history would be

Oliv + Opx + Cpx + Gnt	(subsolidus)
Oliv + Opx + Cpx + Gnt + Liquid	(first liquid; isobaric pseudo-invariant condition)
Oliv + Opx + Gnt + Liquid	(Cpx out; residual garnet harzburgite + liquid)
Oliv + Opx + Liquid	(Gnt out; residual harzburgite + liquid)

All three projections in Fig. 33 suggest that partial melting did not advance beyond the garnet harzburgite + liquid equilibrium, if the starting

material had been average garnet peridotite. With some other, possibly less aluminous mantle peridotite, partial melting may have reached the residual harzburgite + liquid equilibrium.

However, there are objections to this proposed model of magma generation and they are probably more serious than those indicated for the previous cases. Fundamental to the objections is that the Group II compositions bear no special relationship to the 40 Kb. cotectic curves, thereby implying that at least part of the evolution of the magma took place in some other pressure environment. The evolution of the 40 kb. liquid required, so that it might become coincident with the plotted positions of the parental Baffin Bay lavas, would need to involve not only co-precipitation of olivine and orthopyroxene (a condition not readily obtained, considering that all primary phase volumes contract to the advantage of olivine when the pressure is lowered) but also preferential removal of the orthopyroxene while olivine was retained. The magma would then have to erupt in this evolved condition, bearing only the characteristics of its most recent depth of equilibration (or its attempt to achieve it), and leaving its previous, higher pressure history open to speculation in the absence of any other evidence.

D) Conclusions

In Chapter 3 it was suggested that the observed differences in chemical composition between the two suites could be explained by a higher degree of partial melting of mantle peridotite for the Baffin Island parental magma. This scheme still remains as an alternative to the operation of eclogite fractionation on the Svartenhuk parental magma, but evidence against variable degrees of partial melting includes the following:

- 1) the lower degree of partial melting for the Svartenhuk magma, indicated by

the incompatible elements, has then to produce an erupted volume several orders of magnitude greater than the volume on Baffin Island, and vice versa

- 2) since a relatively high degree of partial melting is already suggested by the low levels of incompatible elements (probably into the liquid + residual harzburgite equilibrium), all the sodium and potassium should be in the liquid at that stage, and therefore there should be no difference in the $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios of the two batches.
- 3) the high level of some incompatible elements in the two nepheline normative specimens, especially 598, suggests that they could be the products of a mild degree of eclogite fractionation (see section VI)

This evidence is not conclusive in ruling out degree of partial melting as the cause of the differences in minor element content, but the model of subsequent evolution of the magmas becomes very complex.

Thus, in spite of the limitations imposed by the current paucity of high-pressure melting relations, it has been possible to advance a theory for the pre-eruptive history of the Baffin Bay basalts. Returning to the four limitations and requirements demanded by the chemistry and petrography of the rocks, it has been shown that fewer violations accompany the preferred case of 30 kb. partial melting than accompany the rejected ones. The requirement for a high degree of partial melting has been satisfied, as has the need for limiting or eliminating fractionation of the magma by rapid ascent en route to the surface, and the required conditions were met for eclogite fractionation to operate on a portion of the magma at depth. The relative simplicity of this model is also in its favour, although simplicity is probably a poor criterion to apply when dealing with what is, after all, a multicomponent, open and polybaric system. Nevertheless, the end product,

the lavas, do have simple primitive compositions, and any complexities introduced into the system during its evolution (including the small degree of eclogite fractionation) must only serve to diminish that primitive character. Therefore, it is suggested that the Baffin Bay magmas consist first of primary compositions derived directly from advanced partial melts at a depth of approximately 100 km. (Baffin Island parental magma), secondly of compositions modified somewhat at high pressure (Svartenhuk parental magma), and finally of compositions which evolved in low-pressure, high-level magma chambers (olivine-poor basalts of both provinces and feldspar-phyric basalts of Svartenhuk). It is this last category which still remains to be discussed and will be considered in a subsequent section.

VI. Nepheline-Normative Specimens

Samples 598 and 641 contain 1.30% and 0.20% normative nepheline respectively. All the other specimens are hypersthene-normative and are thereby classified as tholeiitic in the terminology of Yoder and Tilley (1962). What must be considered is whether these two specimens of "alkali basalt" may be accounted for in terms of alteration, both being collected at sea-level.

Sample 598 has an unusual alteration of olivine to serpentine and chlorophaeite(?) and is also characterized by an unusually high water content. The combination of high H_2O^+ , K_2O and Sr (Table 2) is reminiscent of some of the breccias of Baffin Island (RBB, ROB); so the possibility of contamination by sea-water cannot be ruled out. Sample 641 appears fresh in thin section but is characterized by a slightly higher value for Na_2O (Table 2) compared with other samples of a similar MgO level. Again a small amount of sea-water with dissolved NaCl might be sufficient to produce the small amount of nepheline in the norm.

While it is simplest to regard these two flows as being contaminated, the presence of late-stage alkaline differentiates in Ubekendt Island (Drever and Game, 1948; Drever, 1958) should be taken into account. Their presence means that at some stage, in the intermediate- or high-pressure range (O'Hara, 1968), some of the basaltic magma must have entered the nepheline-normative volume. The nepheline basalts and monchiquitic basalts of Ubekendt indicate that at least some of this magma was retained at elevated pressures long enough to become so undersaturated as to be able to crystallize undersaturated minerals. However, there is no reason why some of the material could not have been erupted at an early stage of entry into the nepheline-normative volume. The implied delay of ascent makes it significant that samples 598 and 641 occur well to the southwest in the peninsula.

VII. Rate of Magma Ascent

As a prelude to the discussion of high-level fractionation, some further comments should be made on the subject of transport of the magma to the surface. A rapid rate of ascent is implied by the skeletal habit, small size and profusion of olivine phenocrysts, the low level of incompatible elements and the failure of the early bulk compositions to attain equilibrium at 1 atmosphere. Given such an apparent rapid rate of ascent, it is perhaps surprising that there are neither xenoliths of fertile mantle nor of residual barren mantle in either province. This absence, at least, appears to be merely a characteristic of tholeiitic provinces. The absence of high-pressure cumulates has been mentioned in a previous section, and the fact that there are no intermediate-pressure cumulates, such as lherzolite, may mean that once ascent was initiated it was both steady and fast enough to keep the bulk composition of the magma well within the primary phase volume of olivine.

Therefore, the opportunity for forming lower-pressure cumulates was never created. The absence of even dunitic cumulates, apart from the occasional glomeroporphyritic cluster of olivine, again suggests that the magma was at no time static enough even to allow accumulation of its increasing olivine phenocryst load.

Murata and Richter (1966) have estimated that the rate of settling of olivine crystals (3 mm. diameter; 3.4 gm./cc.) in a basaltic magma (2.77 gm./cc.; viscosity 2×10^3 poises) would be about 0.5 metres per day. Therefore, in order for the magma to arrive at the surface complete with all phenocrysts crystallized en route, the rate of ascent should never drop below this figure, although the smaller size of olivine phenocrysts in Baffin Bay parental lavas could permit slower rates of ascent. Since at least some of the magma arrives at the surface with its liquid composition still in the primary phase volume of olivine, the cooling rates must therefore not exceed approximately 10^0 per kilobar in the case of partial melting of garnet peridotite in the pressure range 20-40 kb. In order to calculate the rate of ascent required to remain within this limit, both the geothermal gradient and thermal conductivity of the surrounding rocks would have to be known, as well as the thermal coefficient of adiabatic expansion of basaltic magma. All that can safely be said about the rate of ascent is that it must have been faster than most other basalts, which tend to be erupted with two or more phenocryst phases.

One further aspect arising from the work of Murata and Richter (1966) is that some of the most picritic compositions also tend to have the largest olivines (e.g. DX-52 11 mm.; 512 10 mm.; 593 8 mm.; 640 8 mm.). Of these, both the DX-52 and 593 flows were only 3 m. thick. Murata and Richter have shown that eruption of the most picritic compositions in Hawaii are accompanied by high rates of discharge and apparent sweeping out of the olivine cumulus on

the floor of the magma chamber. This feature of periodic eruption of cumulus-enriched magma is also demonstrable in the Baffin Bay basalts, and this may indicate that high-level magma chambers were in existence in both provinces. This mechanism of occasional paroxysmal evisceration of magma chambers may be the explanation for the low fayalite content of the olivines (Fa_8) in flow 593, which was collected near Arfertuarssuk. In that area the differentiation should have been well advanced; in fact, the transition to feldspar-phyric basalts occurs in this region, but if very early, forsteritic cumulus had been disturbed then this anomalous flow would be explained. The alternative to this suggestion is that sample 593 was simply collected from a flow on the eastern side of a fault block which had been tilted southwest, and consequently a very early flow was exposed. Neither of these possibilities can be tested at the present time. Another consequence of the idea of high-level magma chambers is that, if the periodic violent evisceration continued during the eruption of feldspar-phyric basalts, then the production of "grey flows" relatively enriched in mafic minerals might take place. This possibility will be investigated in a following section.

VIII. Advanced Differentiation

Four aspects of advanced differentiation will be considered in turn. These are (i) the development of intra-flow differentiates; (ii) the development of the feldspar-phyric basalts of west Greenland; (iii) the origin of the trachytes and other salic residua, insofar as they have already been regarded as late-stage fractionates of the basalts (Drever and Game, 1948); and finally (iv) the carbonate-rich material.

A) Intra-flow Differentiates

The development of intra-flow differentiates is a feature sometimes found

in the rare thick flows of picritic composition. On Baffin Island the late-stage leucocratic material produced in these flows represents the most evolved compositions in the entire province, whereas the bases of the same flows are frequently the most picritic. Only one such flow has been examined on Svartenhuk, and its leucocratic differentiate is in many respects intermediate in composition between the picrites and the feldspar-phyric basalts. Also, Munck (1945) has described strong internal differentiation of two gabbroic sills on Nugssuak Peninsula, but none was observed on Svartenhuk.

The original olivine basalt magma was obviously fluid enough to permit settling of both the olivine phenocrysts and later olivines which had crystallized in situ. The texture developed in the picritic portions of the flow is that typical of olivine cumulus in an intercumulus matrix of plagioclase, clinopyroxene and interstitial material (Plate VI). A gradual decrease in the content of olivine from near the base of the flow (approximately 50%) to the top (approximately 2%) is easily detectable in the field. Results of X-ray diffractometer studies on two olivines from the thick flow at Cape Dyer suggest that the expected cryptic layering may also exist. The olivines from sample AA-30 gave $Fa_{18.6}$, and sample A-5, about 6 m. higher in the flow, gave $Fa_{19.3}$.

That settling of olivine was principally responsible for the observed compositional variation may be seen from Fig. 7, in which the parts of intra-flow differentiates are indicated. To further illustrate that olivine has been responsible for the observed chemical differences, the amount of olivine removal needed to produce each differentiate from its parents has been calculated from Fig. 24. The results are presented in Table 10, and it may be seen that there is a fair measure of correlation between the enrichment factor expected on the basis of olivine fractionation and the average enrichment

Table 10 Enrichment Factors of Incompatible Elements in Intra-flow Differentiates

A Olivine-Rich Portion of Flow	B Intra-flow Differentiate	A B Wt. % Removed as Olivine	Predicted Enrichment Factor	Actual Enrichment Factor						Avg. of Previous Six Enrichment Factors	Ni _A /Ni _B
				K_2O_B/K_2O_A	TiO_{2B}/TiO_{2A}	P_2O_{5B}/P_2O_{5A}	Ga_B/Ga_A	Y_B/Y_A	Zr_B/Zr_A		
512	513 ⁺	52	2.1	1.0	2.0	1.9	1.9	2.4	1.7	1.8	4.7
A-5	A-6	49	2.0	2.3	1.8	2.0	2.5	2.4	1.5	2.1	4.3
AA-26	AA-19	56	2.3	2.2	2.2	1.8	2.5	1.3	1.8	2.0	7.6
AA-30	AA-63	60	2.5	1.5	2.2	1.7	2.1	2.2	1.6	1.9	14.3
PP-18	PP-10	24	1.3	1.2	1.6	1.2	1.5	1.9	1.2	1.4	5.5
R-13	R-16	50	2.0	1.8	1.7	1.3	2.2	2.0	1.5	1.8	9.1

Predicted enrichment factor is based on weight fraction removed as olivine from the picritic base of the flow (A) to produce the leucocratic differentiates.(B).

factor of six incompatible elements. The last column demonstrates that the rate of decrease of Ni over the same interval has been two to seven times greater than the rise of incompatibles, strongly suggesting that olivine fractionation was mainly responsible.

Coupled with the build-up of the analyzed incompatible elements must also have been a similar degree of concentration of the equally incompatible volatiles, and the highly vesicular upper reaches of the flows testify to this enrichment. Periodic concentration and release of volatiles through the top crust of the thick flow may have occurred, since olivines of the upper part of the flow (but not the already solidified lower part) are characterized by oscillatory and concentric development of iddingsite and fresh olivine (Edwards, 1938).

Relatively thin bands of leucocratic material with predominantly near-horizontal attitudes are frequently found in the upper parts of the olivine-rich portion of thick flows. The contacts between the two rock types are unchilled, and the sizes of the vesicles in these leucocratic bands are larger than those found even near the top of the flow. It is believed that during periods of high concentration of volatiles in the upper part of the flow, the magma became extremely fluid and was forced into joints produced by cooling and contraction of the solidified olivine-rich part of the flow. The long, almost skeletal grains of plagioclase and clinopyroxene in the leucocratic bands suggest that the magma was injected largely as liquid and that these grains have grown in situ.

The projected positions of the intra-flow leucocratic differentiates in Figs. 22-24 require an explanation. The leucocratic material plots well within the plagioclase primary phase volume but nevertheless still along olivine control lines from the bases of their respective flows. Simple olivine

removal from the parent magma can take the composition of the liquid down temperature to the cotectic line represented by the equilibrium Oliv + Plag + Liquid. In order for the bulk composition to continue to move away from the parent on an olivine control line, olivine must begin to be preferentially lost in that 3-phase equilibrium. Gravitative settling of olivine is the most striking feature of the thick differentiated flows, and the only assumption that has to be made is that conditions prevailed to allow the flotation of plagioclase once it began to crystallize. This simple method of producing compositions in the plagioclase primary phase volume suggests the method by which the feldspar-phyric basalts may have formed.

B) Feldspar-phyric Basalts

A summary of the order of appearance of phenocryst phases in the Svartenhuk basalts is given in Fig. 34, where the phenocryst assemblage is plotted against the Thornton-Tuttle (1960) differentiation index. It may be seen that the silicate phases appear in the order olivine, plagioclase and clinopyroxene.

Magnetite is the first phenocryst phase to appear after olivine, but its sporadic occurrence suggests that its formation is probably dependent on variable conditions of oxidation prior to or during the time of eruption. Apparently, the liquid occasionally encountered a fluctuating field of magnetite crystallization, probably controlled by local, unstable conditions of partial pressure of oxygen. The more frequent occurrence of serpentine pseudomorphs after olivine in the Svartenhuk picrites and olivine basalts, coupled with the hint of opaque phenocrysts in one or two dykes on Baffin Island, suggests that dissociation of water and subsequent oxidation of the magma may have been the mechanism governing the formation of magnetite. This is, at least, a realistic suggestion, since convincing field evidence exists to suggest that

Fig. 34. Appearance of Phenocryst Phases in the Basalts of Svartenhuk Peninsula.

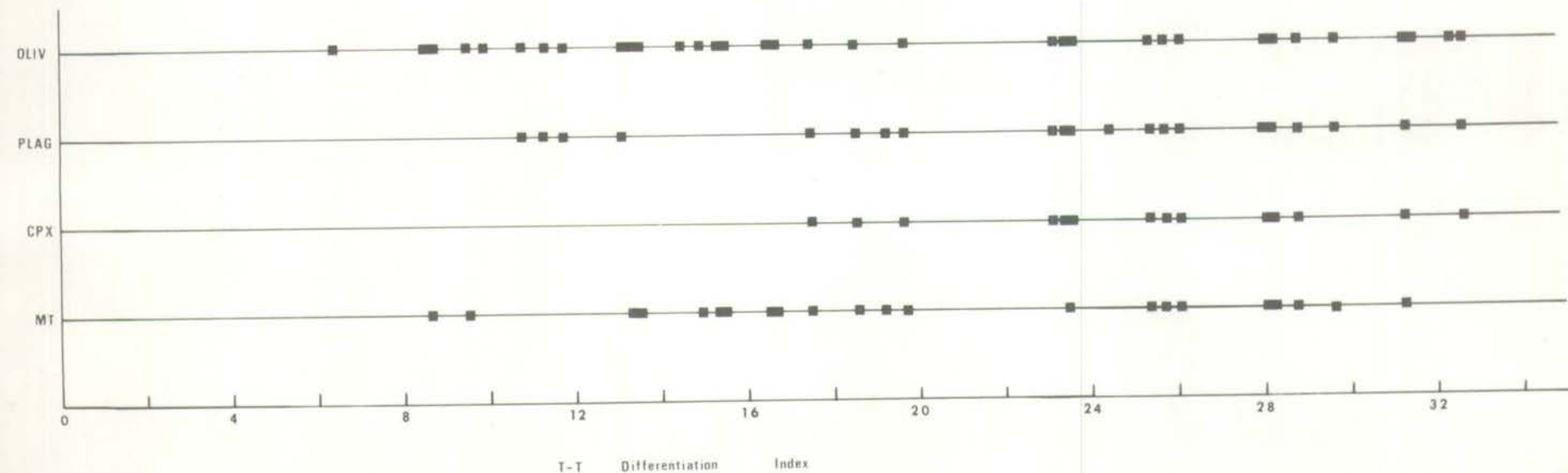


FIG. 34

the Svartenhuk magmas ascended through a thicker column of wet sediments than did the Baffin magmas. In the early stages the two assemblages, olivine + plagioclase and olivine + magnetite, appear to be mutually exclusive. A high water vapour pressure, with the consequent possibility of increased ppO_2 , could have the combined effect of suppressing the crystallization of plagioclase and favouring the formation of magnetite (Osborn, 1963).

In spite of some reversals, the general trend is towards the development of four phenocryst phases in the later basalts, although olivine becomes invariably pseudomorphed in the late feldspar-phyric basalts. The generally low levels of SiO_2 , relative to MgO and FeO , and of P_2O_5 preclude the formation of phenocrysts of orthopyroxene and apatite respectively.

Sample 520 from the base of the section of feldspar-phyric basalts has a differentiation index of 23.1 and represents the most primitive of these compositions to be erupted. From this stage onwards, most of the basalts appear to be evolving in the equilibrium Oliv + Plag + Cpx + Mt + Liquid, possibly a pseudo-quaternary invariant point, and the process of crystal-liquid fractionation must now involve all of these phases. With reference to Fig. 7, it may be seen that the entry of the feldspar-phyric basalts at the 6-7% MgO level initiates marked downward trends in SiO_2 , Al_2O_3 and CaO and upward trends in total iron, TiO_2 , Na_2O , K_2O and P_2O_5 . This may indicate that addition or removal of plagioclase is now the predominant mechanism by which compositions are varied. Nevertheless, there would be considerable scatter about any proposed plagioclase control line, and this must presumably result from the effects of small differences in olivine, clinopyroxene and magnetite phenocryst content. For the most part, the rapid build-up of iron in the residual feldspar-phyric basalts (Figs. 7, 15) suggests that magnetite either has been acting as a non-fractionating phenocryst (Cox et al., 1967) or, at least, has been settling out of the magma in a proportion less than its concentration in the liquid.

The strong concentration of incompatible elements in these residual liquids, which have relatively stationary bulk compositions, indicates that the liquid must indeed be evolving at or near an invariant point. There the major element bulk composition will remain static, while incompatible elements will appear to have their rate of increase accelerated. Correlation coefficients between some of the elements are given in Table 11, where many of the incompatible elements which were previously weakly correlated in the olivine basalts are now strongly positively correlated. As before, the strong positive correlations are based on mutual exclusion from precipitating phases, which therefore must include only small amounts of TiO_2 , K_2O , P_2O_5 , Ba, Sr, Rb, Y and Zr. Copper and zinc also have the appearance of being rejected from crystallizing phases, presumably as a result of low concentration of sulphur in the liquid.

Turning now to the phase relations in the simple normative basalt tetrahedron (Figs. 21-24), it may be seen that the mechanism for the derivation of the intra-flow differentiates may also account for the evolution of the feldspar-phyric basalts. Many of the feldspar-phyric compositions may be accounted for in terms of fractionation of olivine from a Group II olivine basalt parent to the point where plagioclase is picked up as second phase. At that point, selective removal of olivine, and flotation of plagioclase in that equilibrium, would account for the early feldspar-phyric basalts. Within a small cooling interval, clinopyroxene would also enter the equilibrium (Fig. 24). This would then provide a further means of producing compositional variation by selectively removing Oliv + Cpx and thus driving the remaining bulk compositions towards the Flag corner.

The continuity of all trace elements (whether positively or negatively correlated with MgO) from the olivine basalts through the feldspar-phyric

TABLE 11

Correlation Coefficients between Components
of Feldspar-phyric Basalts of Svartenhuk

P_2O_5			0.97				
Cr_2O_3	-0.76		*	-0.73			
Zr			*	0.95			
Sr		0.74				0.74	
Ba		0.92				0.78	
Y			*	0.76		0.74	0.74
	FeO	K_2O	TiO_2	P_2O_5	Rb	Cu	Zn

* - denotes significant correlation coefficient reported in Table 4

basalts supports the hypothesis that a single evolving magma was responsible for the entire range of basaltic compositions found in the vicinity of Baffin Bay. Had the feldspar-phyric basalts belonged to an independent line of evolution, the continuity of all the minor element trends would not have been expected to occur. Therefore, the conclusion can be drawn that a single melting event in the mantle produced a discrete magma batch, a proportion of which was quickly erupted as the fluid picritic and olivine-rich basalts, and the remainder more sluggishly erupted as the thick feldspar-phyric flows.

Earlier a case was made for a small degree of eclogite fractionation of the parental Svartenhuk magma. It is evident from the minor element content of the feldspar-phyric basalts that they are not a separate portion of the primary magma at 30 kb. which might have remained at depth to undergo further eclogite fractionation. O'Hara and Yoder (1967) have listed the chemical changes which would take place under eclogite fractionation and, while the differences between average Baffin Island and average Svartenhuk olivine basalts agree with the predicted changes, the differences between Svartenhuk average olivine basalt and average feldspar-phyric basalt do not. High-pressure evolution of the feldspar-phyric basalts is thus ruled out, as is fractionation at intermediate pressures, where the residual liquid would be driven into the nepheline-normative volume (O'Hara, 1965, 1968). The only remaining pressure regime is that of low pressure (less than 10 kb.), where the liquid is committed permanently to the hypersthene-normative volume and should eventually produce normative quartz. The precise depth of the magma reservoir where the feldspar-phyric basalts evolved is unknown. Conditions were such that production of oscillatory-zoned plagioclase phenocrysts became a characteristic feature of these rocks, possibly owing to periodic build-up and release of volatiles in the chamber. Also, the conditions of eruption were such that

gabbro xenoliths were never brought to the surface, although the "gray-flows" interspersed in the feldspar-phyric basalts might represent more mafic assemblages swept from the floor of the magma chamber.

C) Trachytes

In Svartenhuk the most differentiated feldspar-phyric basalts were quartz-normative, and it would therefore have seemed likely that any strongly felsic differentiates of this material should be rhyolitic rather than trachytic. Unfortunately, the absence of any intermediate rocks between the basalts and the trachytes on Svartenhuk makes very difficult the proposal of any scheme of fractionation from the former to the latter.

The answer to this problem must eventually come from Ubekendt Island, where Drever and Game (1948) have described an Upper Lava Group consisting of feldspar-phyric basalts, monchiquitic basalts, trachybasalts, biotite trachytes, rhyolites and acid pitchstones. This represents the youngest and most complete suite of late-stage salic differentiates yet recognized in the west Greenland province and provides the best opportunity for studying the evolutionary trends in detail. There is apparently a bias towards hypersthene-normative late-stage products rather than towards alkaline material (J. G. MacDonald, pers. comm.), possibly indicating a predominance of low-pressure over intermediate- or high-pressure differentiation processes.

D) Carbonate-rich Material

Probably the youngest rocks occurring in Svartenhuk, and possibly the final material of Baffin Island, consist of dykes of compositions rich in carbonate. The mineralogy of the Baffin Island dykes includes carbonate and any or all of forsteritic olivine, serpentine, phlogopite, scapolite(?) and

an opaque mineral. In Svartenhuk the carbonate is associated with serpentine, basaltic xenoliths and an unidentified mineral.

In the Padloping area of Baffin Island, a basement gossan, cut by carbonate, has been strongly altered to a sheared, greenish rock at the contact. This alteration is accompanied by the production of considerable graphite, presumably through reduction of carbonate by sulphide minerals. In Svartenhuk, where the carbonate-rich material intrudes into the basalts, there are sheared and metamorphosed contacts, and the dykes are frequently characterized by inclusions of brecciated basalt xenoliths.

Some semi-quantitative chemical work has been done on two or three samples from each province, and the following average values were obtained for Baffin Island and Svartenhuk in that order: Ba < 20, < 20 ppm.; Sr 151, 40 ppm.; Rb < 8, < 8 ppm.; Y 7, 2 ppm.; Zr 21, 28 ppm.; Cr < 20, 90 ppm.; and Cu < 6, 21 ppm. This suite of trace elements does not particularly favour a deep-seated origin for these rocks, i.e. true carbonatites (see Gold, 1963), but it may be significant that the two group averages are roughly comparable and therefore may have at least a common type of origin.

I. Introduction

So far only the stratigraphic similarity and degree of chemical correlation in the two Tertiary subprovinces of Baffin Bay have been discussed. It is now proposed to relate the igneous event to its structural environment. In order to fully understand the tectonic framework, it is necessary to regard the production of basalts as only one of a large number of nearly contemporaneous events which characterized the early Tertiary history of the eastern Arctic of North America, including Greenland. All of these events, when taken together, constitute a persuasive assemblage of evidence in favour of continental drift.

This chapter opens with an historical review of ideas on the topic of continental drift in this part of the Arctic, up until 1960. However, after that year it becomes difficult to make a distinction between papers contributing directly to the solution of the problem of drift and those which are purely geological reports requiring further interpretation in the light of continental drift. In these latter papers there is usually no reference to the subject of drift, and it is such completely unbiased reports which are the most valuable. Therefore, work presented largely since 1960 will be treated in a later section which attempts to compile evidence in favour of continental drift, whether or not that was the original authors' intention. The chapter concludes with the presentation and discussion of a new model for the opening of Baffin Bay and the Labrador Sea.

II. Historical Review to 1960

Du Toit (1937) has published an excellent review of the early years of drift theory, suggesting that the tentative thoughts, which eventually led to

a comprehensive theory, had been appearing in literature for nearly three centuries prior to 1900. After that date, publications on specific aspects of the hypothesis appeared quickly, e.g. the list of geological similarities along the opposing Atlantic coastlines made by Suess (1906). Then two years prior to the publication of Wegener's initial paper on the subject, Taylor (1910), although more concerned with Tertiary orogeny than continental drift as such, nevertheless produced a remarkably lucid account of his ideas on the break-up of the continents in Arctic regions. So many of the ideas believed to be novel to later authors are in fact anticipated in Taylor's paper. These include consideration of the Robeson channel which separates Ellesmere Island from northwest Greenland as a "rift-line"; a rift origin for Hudson Strait, Foxe Channel, Gulf of Boothia and Lancaster Sound; and a movement of Baffin Island independent of North America and Greenland. He even went so far as to state that the "parting of these shores can hardly be more recent than the Tertiary, nor is it easy to believe that it is much older". It must be rare in the geological world that the first speculative application of a new theory on a regional scale, based on scanty and often unreliable information, can still be largely upheld nearly sixty years afterwards. Later, Taylor (1928a, b) on the one hand made a very reasonable estimate of the rate of drift, i.e. 1-3 cm. per year, but on the other made an implausible appeal to catastrophic capture of the moon by the earth in Cretaceous times, which, he said, would have provided the necessary tidal forces to move the continents.

Wegener published many papers after 1912, but it was not until 1924 that the third edition of his book was finally translated into English. In spite of the criticism regarding his timing of the rifting of the continents and the resulting rate of movement, he remained entirely convinced of the idea that

all the continental masses, including the various blocks in the Arctic, had been greatly displaced. Unfortunately, Wegener's enthusiasm led him to propagate some unreliable evidence which was to discredit the theory for many years. It was in the symposium under van der Gracht (1928) that Wegener came under heaviest criticism, mainly on geophysical grounds and on the accusation of unscientific presentation. But in spite of the collection of specific objections raised in the symposium, most of the contributors were prepared to accept the theory if given more and better evidence.

The untimely death of Wegener in 1930 slowed the pace of further investigation for many years. About this time Holmes (1928, 1933) presented the first detailed considerations of the possibility of moving continents by means of thermal convection cells in the mantle. He suggested that horizontal flow could exert a powerful viscous drag on the lower crust, which would result in tension rifts appearing, followed by actual physical separation. He was also convinced that the leading edges of the continents were the sites of the world-encircling belts of Tertiary orogeny.

Du Toit (1937) demonstrated an ability for treating structural problems on a global scale. It was he who first suggested the piecing together of the fragments of "Thulean" lavas by restoration of the continents to their original positions. "Dispersal by Drifting would not only solve this difficulty, but demand a parent volcanic region having only a fraction of the size currently conceived." He was also convinced that the rifting and volcanism were closely associated. This same point was emphasized by Wager (1947), when he remarked on the synchronous commencement of eruptions in the widely scattered Brito-Arctic remnants and dismissed the possibility of its being due to pure coincidence.

Kranck (1939) was the first to begin compiling data along both coasts of the Labrador Sea, with the aim of investigating the case in favour of drift.

He concluded that "there seems to exist a good correspondence as regards geological events during the Pre-Cambrian time on both sides of the Labrador Sea".

The current revived interest in continental drift stems from the discovery of palaeomagnetism as a useful tool in deciphering the paths of former continental movements (Graham, 1949). A summary paper on palaeomagnetism is given by Irving (1958) in a symposium organized by Carey. In the same volume Carey himself coined many of the words which have become incorporated in the current jargon, including "orocline" and "sphenochasm". Carey's idea on the formation of the Alaskan orocline was ingenious but unfortunately premature, since more recent information collected in the Arctic Ocean is inexplicable in terms of his model for the opening of the Arctic. However, the principles are useful, and a similar but more limited application of them is employed by the present author in his theory of the opening of Baffin Bay.

III. Compilation of Information Regarding Continental Drift

A) Palaeontology

As a result of the paucity of Phanerozoic rocks in most of west Greenland and eastern Canada south of Lancaster Sound, there is very little that palaeontology can contribute towards a solution of the problem. However, the very absence of such rocks indicates that the entire region was probably a stable cratonic shield for the 1200 my. prior to the Tertiary volcanic activity, and this in itself is significant. In spite of the scarcity of fossiliferous sediments, where they do occur they have provided useful information. As already mentioned in Chapter 2, Rosenkrantz (1942) and Birkelund (1965) have demonstrated the non-existence of a marine connection southwards from Disko before Upper Santonian times, but after that stage a connection

southwards to the European Cretaceous seas was established. The interpretation which may be placed on this event is that the Labrador Sea and Baffin Bay were only beginning to open up at that time. (Larsen and Møller (1968) report the presence of some dykes in the Frederikshaab area of southwest Greenland with a radiometric age of 162 ± 5 my., or Middle Jurassic, and this may be construed as further evidence that tension began in the south and moved northwards.)

The other palaeontological evidence is provided by Trumpy (1961), following from his work on the Triassic of northeast Greenland. He has demonstrated that the Triassic sea of east Greenland was only a narrow arm of an Arctic ocean which had a blind southern ending in the vicinity of Scoresby Sound. He concluded that "there is no direct proof for the existence of a North Atlantic Ocean in the Triassic (or, indeed, up to the Cretaceous)," the implication being that continental drift had not yet begun in the northern regions. Vine (1966) has shown that even an opening of the North Atlantic in Palaeocene times requires an average rate of drift of only 2 cm./year, so that Trumpy's conclusions appear reasonable.

B) Palaeomagnetism

Bidgood and Harland (1961) have shown that Greenland pole positions indicate "a movement of Greenland relative to North America which increased the separation of the two areas to give their present positions, that is, mainly by the opening of Davis Strait and Baffin Bay and by some spread among the Canadian Arctic Islands. The movement would be post-Triassic in date."

C) Geophysical Studies in the Labrador Sea and Baffin Bay

Geophysical exploration of the Labrador Sea properly began with the work

of Ewing and Ewing (1959). They shot one seismic refraction profile from $54^{\circ}27'N.$, $43^{\circ}19'W.$ to $55^{\circ}12'N.$, $42^{\circ}30'W.$ and established that along that line continental crust was absent. Their computed model gave 1.06 km. of unconsolidated sediment followed by at least 5.50 km. of oceanic crust. Heezen and Ewing (1961, Fig. 2) indicated the presence of a mid-ocean canyon in the Labrador Sea. Further seismic work was done by Drake et al. (1963), using the continuous profiling technique. They were able to show the following important features: (i) the sedimentary cover on the sea floor, especially near the continents, is extremely thick; (ii) sediments cover the entire sea floor, but at the geographic centre of the sea the 5.5 km./sec. "basement" rises to within 1 km. of the sea floor at $61-62^{\circ}N.$, actually outcropping as isolated peaks south of these latitudes and therefore, there exists a buried topography of some magnitude; and (iii) the seismic refraction data suggest a complex structure more like that of the mid-Atlantic ridge than of typical ocean basin.

Data on earthquake epicentres have been summarized by Meidler (1962) and Sykes (1965). The range in magnitude on the Richter scale is from 3.5 to 7.3 for the Labrador Sea and Baffin Bay; and depths of the focal points, while not known for certain, are believed to be shallow, i.e. <70 km. The epicentres define a rough line through Baffin Bay and the Labrador Sea, with two noticeable concentrations at $61^{\circ}N.$ and $73^{\circ}N.$, and in the proposed model some significance is attached to these. A single explanation will be advanced to account for both the clustering of epicentres and their geographical "off-centredness" in Baffin Bay. In any case, there is no doubt that this is a seismically active area even though the frequency of earthquakes is only about 10% that of a "normal" active oceanic ridge, e.g. the mid-Atlantic ridge or East Pacific rise. For this reason and other reasons following, it would seem necessary to regard the present structure as being in a state of old age.

Fig. 35. Geophysical Data in the Labrador Sea.

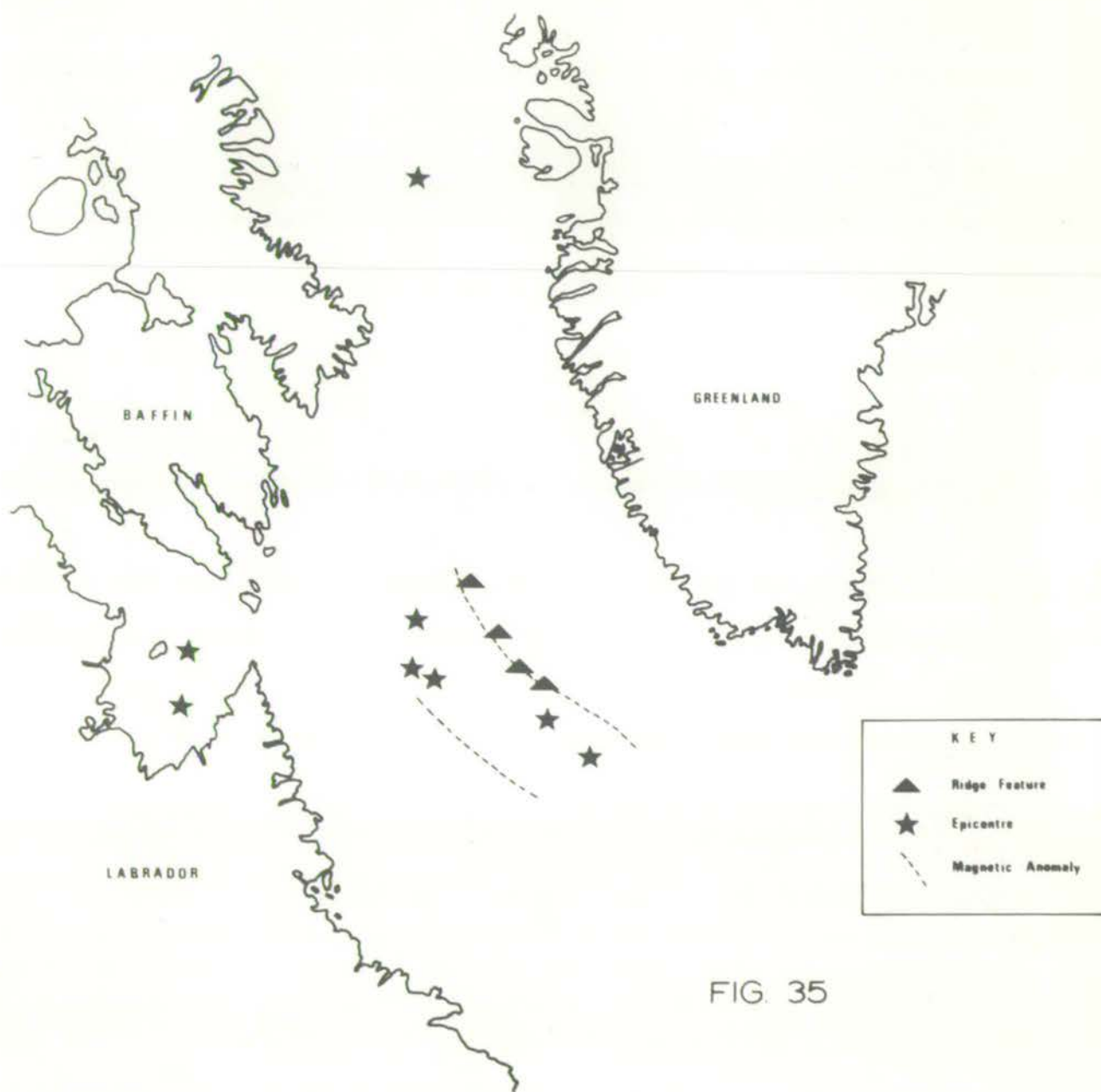


FIG. 35

Aeromagnetic work in this region began with Hood and Godby (1964) and has been continued by Godby et al. (1966) and Hood et al. (1967). The pattern of linear magnetic anomalies found running parallel to the geographic centre-line of the Labrador Sea is strongly reminiscent of similar patterns developed on the flanks of ridges in other ocean basins (cf. Vine, 1966). Although the work of Godby et al. (1966) is not yet complete, their preliminary conclusion is that "the line of epicenters in the central part of the Labrador Sea bounded on either side by zones of parallel magnetic anomalies and additional seismic refraction and profiler evidence appear to support the hypothesis that there is an active buried median ridge in the Labrador Sea which is further evidence for a continuing continental drift between Greenland and North America."

Johnson and Pew (1968) have been able to position the basement ridge more accurately and have placed it somewhat to the east of a line which bisects the distance between opposing continental shelf-breaks. They concluded that their seismic reflections do not permit the existence of continental material in the Labrador Sea, contrary to the statements of Kerr (1967a). Their interpretation of the available geophysical data, summarized in Fig. 35, is that the basement high may represent the eastern belt of rift mountains, with the seismically active central band representing the ancient rift valley. The lack of an axial magnetic anomaly may be due to the blanketing by sediments or formation of the central band during a period of reversed polarity, but in any event the ridge must be regarded as extinct, or nearly so (Vine, 1966).

D) Geophysical Studies in Lancaster Sound

Gregory et al. (1960) proposed that Lancaster Sound should be regarded as a fault on the basis of a strong magnetic discontinuity at the southeast corner of Devon Island. Other evidence pointing to this conclusion includes

the steep linear coastline of Devon Island, the steep submarine sides of the channel, the left-lateral offset of the Boothia Arch (Gregory et al., 1961) and of the Brodeur-Devon homocline, and the stratigraphic uplift of the north side of the channel by up to 8 km. in Devon and Bathurst Islands (Gregory et al., 1960; Fortier et al., 1963; Barrett, 1966). This upthrow on the northern side would explain the Precambrian basement type of regional magnetic anomalies on Cornwallis Island and southwest Devon Island.

Barrett's (1966) detailed shipborne magnetometer survey of Lancaster Sound led to the conclusion that the north side of the channel has been upthrown by about 8 km. and, in the vicinity of Devon Island, at least, with regional dips westward, this also produced an apparent left-lateral offset of the same magnitude. However, the observed sinistral offset of the Brodeur-Devon homocline and the Boothia Arch is more like 50 km., and so it may be necessary to include also a component of horizontal movement. Other evidence which would suggest transcurrent movement on this lineament is implied by its extrapolation into the Barents Sea, where it defines a marked westward displacement of the northern side of the continental shelf-break. This feature is well authenticated by Cromrie (1961) and Plouff et al. (1961) and leads to the speculation that the entire triangular block of Ellesmere Island-Devon Island-Prince Patrick Island may have behaved as a unit.

E) Jigsaw Fit and Structural Consequences

The classical method of continental reconstruction has been to reassemble the fragments in the manner of a jigsaw puzzle. Bullard et al. (1965) were the first to apply an objective, mathematical technique to the continental shelf-breaks, involving rotation about a point near the North Pole, in order to position the subcontinent of Greenland against North America. In spite of

TABLE 12

Correlation of Structural and Igneous Provinces across
the Labrador Sea and Baffin Bay

<u>Mean Radiometric Age (my.)</u>	<u>Eastern Canada</u>	<u>West Greenland</u>
55	Brito-Arctic Province	Brito-Arctic Province
1000	Grenville Province	-
1230	-	Gardar (1335-1150)
1370	West Nain Province Elsonian Orogeny (1620-1180)	-
1590	Churchill Province Labrador Trough (1650-1560)	Ketilidian Orogeny (1640-1500)
1730	Churchill Province East Coast (1790-1610)	Nagssutoqidian Fold Belt (1790-1650)
2100	East Nain Province (2670-1570)	Central Basement Gneiss Unit (2610-1810)

2570

the geologically oversimplified method of pure rotation, the fit is remarkably good south of Hudson Strait, and this positioning will be used as the starting-point in generating a new model for the separation of Greenland from North America. The limitations of Bullard's fit are obvious, especially the enormous width of Nares Strait created in his model and the presence of undesirable overlap in the neighbourhood of Davis Strait, both of which require rectification. Magnetic work by Keen et al. (1966, unpub.) and Hood (pers. comm.) suggests an extension of the Tertiary basalts into the strait, a feature which would have greatly enlarged the continental shelves and would now be responsible for the observed overlap.

That the jigsaw fit is not merely fortuitous is borne out by the strong degree of geological correlation between Labrador and the repositioned Greenland. This has been discussed by Fitch (1965) and Harland (1965, 1966), who have demonstrated that the various orogenic belts have continuity across the rift. These periods of orogeny can be very precisely defined by plotting the abundant age determinations available in Wanless et al. (1966), Larsen (1966), Larsen and Møller (1968) and Jørgensen (1968). In this way, many similar structural provinces can be recognized and these are summarized in Table 12.

Even smaller-scale elements become aligned in this reconstruction. Bridgwater (1967) has remarked on the possible extension of the fault zone controlling Gardar intrusions from southwest Greenland into Labrador, where faulting controls the location of similar, possibly contemporaneous, intrusives (Wheeler, 1960).

F) Structural Evidence

If late Mesozoic-early Tertiary structures exist along the entire length of the Labrador Sea and Baffin Bay, it is only possible to recognize them as

such in the Cretaceous-Tertiary rocks of Baffin Bay. In west Greenland Rosenkrantz and Pulvertaft (in press) have described an episode of normal faulting which defined the eastern limit of the basin of contemporaneous terrestrial and marine sedimentation. Repeated faulting kept pace with the rate of sedimentation, so that only in the fault-controlled depression did material accumulate, and the renewing of coastal fault-scarps provided an abundant supply of sediment. Rosenkrantz and Pulvertaft relate this faulting to a much larger event, saying that "the Cretaceous-Tertiary faulting in West Greenland occurred some way inside the continental margin, but it is of the type expected towards the borders of continental masses which have moved apart." Carey (1958) would call these "second-order gravity faults" occurring near a major tension rift. In short, the timing and the pattern of the Upper Cretaceous faulting, subsidence, sedimentation and finally eruption of lavas onto an area that had been a stable cratonic block for over 1000 my. was indeed a major tectonic event.

However, information obtained in this region is of rather limited value. In fact, it is the structurally complex region to the north of Baffin Bay which holds the key both to the timing and nature of the events occurring farther south. A summary account of the structural history of the Canadian Arctic archipelago is given by Thorsteinsson and Tozer (1960, 1961), and a similar discussion of the neighbouring tectonics of northwest Greenland may be found in Troelsen (1950). A compilation of information from these as well as other authors (Ellitsgaard-Rasmussen, 1955; Fortier et al., 1963; Christie, 1964, 1967; Kerr, 1967b) is presented in Fig. 36, which illustrates the main verifiable structural features.

Briefly, the major pre-Tertiary orogeny occurred in Variscan (late Devonian to middle Carboniferous) times, folding thick accumulations in the Franklinian

Fig. 36. Geological Features in the Vicinity of Nares Strait.

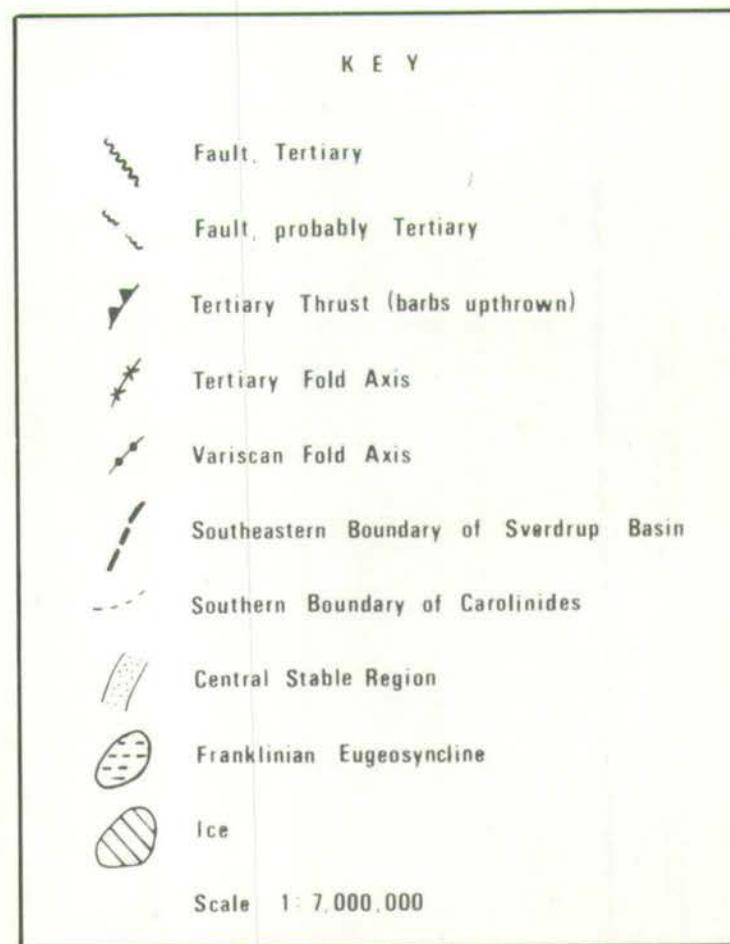
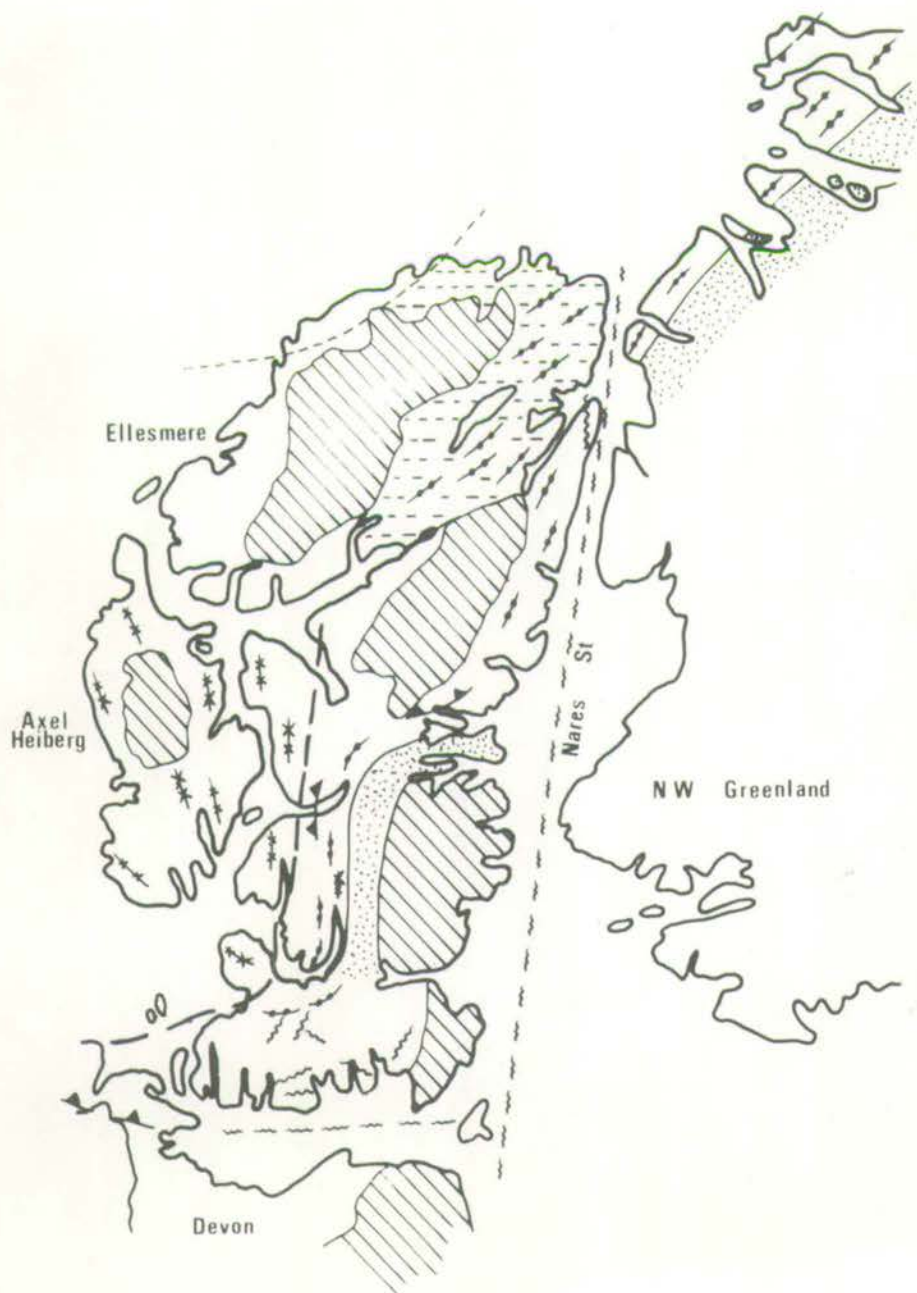


FIG. 36

geosyncline deposited there since the Eo-cambrian. This fold belt is now referred to as the Parry Islands fold belt in the west, the Central Ellesmere fold belt and the North Greenland fold belt. In Canada, Pennsylvanian (Upper Carboniferous) sediments were then deposited, with marked unconformity, onto the folded early Palaeozoic rocks, and sedimentation proceeded almost uninterrupted in what is known as the Sverdrup basin right up to early Tertiary times. In the south and east this basin lies on the beds of the Franklinian miogeosyncline, but in the north and northwest it lies on the eugeosynclinal facies of the same fold belt. At this point the stage was set for the period of Tertiary, so-called Alpidic, orogeny which deformed the Sverdrup basin into the Eureka Sound fold belt.

The timing of this period of folding is generally agreed to be early Tertiary, because it involved all of the Eureka Sound formation, which has been dated as Palaeocene-Eocene (Thorsteinsson and Tozer, 1960; Fortier et al., 1963). The undisturbed overlying rocks of the Arctic Coastal Plain are not sufficiently well dated to provide an upper limit to this age of folding.

The pattern of folding is such that the Sverdrup basin and parts of the previously underformed Franklinian miogeosyncline have been thrown into a radially disposed arrangement of fold axes centred on the reversed L-shaped bend in the Central Ellesmere fold belt. The eastern side of this fold belt is characterized by thrust faulting and deformation of the Franklinian miogeosyncline (Thorsteinsson and Tozer, 1960; Christie, 1967). In Axel Heiberg and Ellef Ringnes Islands the fold axes are aligned nearly north-south and the folding is relatively gentle. Westwards in MacKenzie King Island and parts of Melville and Prince Patrick Islands the amplitude of the folding decreases markedly. Therefore, the Tertiary orogeny is characterized by deformation with diminishing intensity from east to west, with inward-dipping

thrust faults in the eastern region. The principal compressive stress would appear to have been directed from the east.

In southwest Ellesmere Island, in the vicinity of the proposed fulcrum, Kerr (1968) has described the normal faults as being of Tertiary age, but his reasons are not given. The Grinnell thrust fault, dipping north and possibly of Tertiary age (Thorsteinsson and Tozer, 1960), has rejuvenated part of the old Variscan fold belt in northern Devon Island. Similarly, the Copes Bay thrust fault dips inwards towards the Sverdrup basin and is believed to be of Tertiary age (Thorsteinsson, in Fortier et al., 1963; Christie, 1967). In other words, folding in the Sverdrup basin was contemporaneous with mainly thrust faulting on its outer boundaries.

G) Structural Significance of Nares Strait

Without a doubt, the most perplexing aspect of continental reconstruction in the Arctic is whether Nares Strait represents a transcurrent fault, and if not, what sort of geological feature is it? Earlier workers (Taylor, 1910; Wegener, 1924; Du Toit, 1937; Carey, 1958; Wilson, 1963) who tackled the problem of closing the Labrador Sea and Baffin Bay were impressed with the length and straightness of the channel, and did not hesitate to regard it as the trace of an enormous sinistral transcurrent fault. Since more geological and geophysical information has become available, several objections to the earlier hypothesis have been raised, notably by Keen et al. (1966, unpub.) and Kerr (1967b).

Keen et al. report the existence of east-west trending topographic and magnetic features in Smith Sound (southern Nares Strait) which give no indication of having been offset. However, since the data are, by their own admission, sketchy, their findings may only be classified as a warning until

more detailed studies are undertaken. The objection raised by Kerr (1967b) is more substantial and requires close scrutiny. In essence, what he deduces is that stratigraphic considerations do not allow any transcurrent movement on Nares Strait, and he presents an extremely complex model for the formation of the lineament without lateral offset. This mechanism requires the opening of a sphenochasm northwards from the head of Baffin Bay to a point at 80°N. , which becomes a "transform pivot" creating a zone of compression or sphenopiezism beyond. This sphenopiezism is characterized by thrusting and incipient sinistral transcurrent movement, and eventually the whole complex tripartite structure (southern extension, central pivot, northern compression) transforms to a simple rift valley. How the 180° reversal of principal stress direction in the north was achieved is not made clear. Kerr merely states, "Compression existed in the segment north of Lat. 80°N. , and ceased before extension began in that segment". The remarkable linearity of this complex structure is also suspect.

However right or wrong his interpretation is, the value of Kerr's work is that it marks the end of the era when it was sufficient to regard Nares Strait as a transcurrent fault merely on the basis of its length and straightness. Either his interpretation must be regarded as correct or else a better case must be made for transcurrent movement, and this involves a close examination of Kerr's data. Fundamental to his interpretation is a dubious interpolation of isopach contours from various Palaeozoic formations on Ellesmere Island to possible stratigraphic equivalents in Washington Land. These contours are supposed to demonstrate that the units in Washington Land are directly on strike with those in Ellesmere Island, and yet the isopachs change direction by as much as 60° and are projected across the 150 km. of Kane Basin, often through a single data point on the Greenland side. One of the

data points on the Greenland side is in Peary Land, some 600 km. distant from the nearest one in Washington Land. This particular method of correlation appears to be very dangerous and is quite unconvincing.

Kerr's second argument in favour of his rift valley is that Oliver et al. (1955) discovered that at a latitude of 78°N . Nares Strait transmits the Lg phase of earthquake surface waves, which are supposedly transmitted only by continental structures. However, King et al. (1966) pointed out that the Lg phase is not attenuated when traversing less than 100 km. of oceanic crust. The strait is only 80 km. wide from shoreline to shoreline at the point of traverse; therefore, the transmission of this phase is not relevant to the establishing of any particular origin to the strait.

Christie (1964) suggested a lateral offset on the Judge Daly fault zone in northeastern Ellesmere Island. Kerr conceded that "the zone had up to a few kilometers of incipient left-lateral displacement". Then instead of testing this movement as a possible en echelon subsidiary of a major fault zone in the channel, he proffered another explanation based on very dubious structural relations southwards. Having thus dispensed with the Judge Daly fault zone, he revealed that "water-covered extension faults are inferred as responsible for the main outline of Nares Strait north of Lat. 80°N ; however, no extension faults have been reported"; and yet he chose to discount the transcurrent fault that has been reported. Another revelation is that "the inference of normal faulting as the latest structural event in the north is based mainly on the shape of the strait". The shape is, of course, just as well explained by a transcurrent fault, and it would thus appear that no progress has been made since Taylor (1910).

Unfortunately, the state of geological knowledge of this area at the present time is such that a wide variety of interpretations is possible, given

a certain set of assumptions. The dilemma is really provoked by the lack of an indisputable marker horizon or structure occurring on each side of the strait. However, the significant point not dealt with in Kerr's (1967b) arguments is that the episode of Variscan folding is younger than the depositional pattern; it does not conform to any particular depositional pattern; and it is not susceptible to the lateral facies changes which could lead to errors in correlation. If we then attempt to link the structural provinces across Nares Strait, we must only beware of the possible overprinting of some of the Variscan folding (and even unfolded Franklinian miogeosynclinal rocks) by the Tertiary Alpidic orogeny, especially in eastern Ellesmere Island. The areas affected by pre-Tertiary folding in Ellesmere Island have been delineated fairly clearly by Troelsen (1950, Fig. 2), Haller and Kulp (1962, Fig. 2), Fitch (1965, Fig. 4) and Kerr (1967b, Fig. 7). On the other hand, Thorsteinsson and Tozer (1960, Fig. 2) believe that the east coast of Ellesmere Island from Judge Daly Promontory south to Bache Peninsula has been affected by only(?) the Alpidic orogeny. Christie (1964, Map 1148A) indicates that Tertiary folding cannot at least have affected Judge Daly Promontory. Detailed evidence southwards is not available, although Troelsen (1950) states that the Devonian marine strata bordering on Kennedy Channel were deformed in the Variscan orogeny.

The boundary between the Variscan fold belt and the central stable region has been well documented in north Greenland by L. Koch (1929), Troelsen (1950), Ellitsgaard-Rasmussen (1955) and Haller (1961). This structural marker reaches Nares Strait at Hall Land, whereas the same feature on the Canadian side reaches the strait just north of Bache Peninsula. The large measure of agreement on the location of this feature amongst both committed and uncommitted authors suggests that it may be the nearest thing to an actual marker

that is available. If it is accepted that this is a reliable marker, then one is forced to conclude that the sinistral displacement on Nares Strait must be at least 150 km.

In an independent study of large-scale fracture patterns in northern Canada and Greenland, Hilgenberg (1966) concluded that substantial sinistral movement must have occurred along Nares Strait, offsetting what he regarded as an original, regular, rhombohedral pattern of fractures. His restoration of the Greenland pattern to fit that of Labrador required translation along Nares Strait and also involved a shift of Baffin Island westwards to close Prince Regent Inlet, the Gulf of Boothia and part of Foxe Basin.

In addition, Thorsteinsson and Tozer (1960, Fig. 1) showed the boundary between the Palaeozoic miogeosyncline and eugeosyncline emerging at Archer Fiord from the southwest. Extrapolation of its last observed trend should intersect northwest Greenland in the vicinity of Hall Land or Nyboe's Land. In fact, the stratigraphic columns there are dominated by sandstones, arenaceous shales and thick massive limestones (Troelsen, 1950), and although they are not referred to as "miogeosynclinal" it is evident from the facies that they display no eugeosynclinal characteristics. It must be concluded that the Palaeozoic eugeosynclinal deposits lie well offshore to the north of the north coast of Greenland, again suggesting sinistral offset.

Finally, and totally independent of geological considerations, is the finding of Ostenso (1963) concerning the configuration of the total intensity of the earth's magnetic field north of Ellesmere Island. He reported an S-shaped flexure of the 56,000 gamma contour over the linear extension of Nares Strait, indicating a sinistral offset in excess of 100 km. along that lineament. The logical conclusion of these structural, depositional and magnetic arguments is to regard the line of Nares Strait as the locus of a

left-lateral, transcurrent fault, involving a horizontal displacement greater than 100 km.

IV. New Model for the Separation of Greenland from Canada

Until recently there was only one school of thought regarding the movement of Greenland away from North America, and that subscribed to displacement entirely by translation along Nares Strait (Taylor, 1910; Wegener, 1924; Du Toit, 1937; Carey, 1958; Wilson, 1963). The idea is attractive in its simplicity but it fails to account for other major Tertiary tectonic events in the Arctic which were presumably related. Simple translation is also inadequate on the grounds that an increasing degree of separation between Greenland and Canada is required from north to south. Recently, Kerr (1967a, b) has proposed an absence of transcurrent movement in Nares Strait, suggesting that separation took place entirely by continental extension (manifested by normal faulting) and by rotation of Greenland counter-clockwise away from North America. The conclusion of Kerr's argument (1967a), concerning the presence of a continental remnant in the Labrador Sea, has been shown to be invalid by Johnson and Pew (1968). Nevertheless, the mechanism of rotation is necessary in order to generate various other tectonic features in the Arctic archipelago. It is felt that a reasonable compromise should be struck between the two extreme views - pure translation and pure rotation - in constructing a new model for the separation of Greenland from Canada.

The problem of selecting an initial configuration of the continents before drift began has largely been resolved by Bullard et al. (1965, Fig. 7). The position of southwest Greenland against Labrador in Fig. 37 is nearly identical to their fit of the continental shelves. However, it is modified in the north so that Baffin Island is compressed back towards the mainland and

the volcanic province, which was non-existent before Tertiary times, is removed. These alterations are geologically justifiable and serve to eliminate the sizable overlap of continental shelves which Bullard et al. (1965) reported in Davis Strait. (It should be pointed out that although their mathematical fit of bathymetric contours was achieved by rotation only, the centre of rotation located at 88.5°N. , 27°E. is geologically meaningless.) Kerr (1967a) indicated that attempts at reconstruction must also compensate for extension of the continents by normal faulting, so that, in a sense, the fit of Bullard et al. (1965) does not represent the minimum separation of any two points on the opposing continental blocks. In other words, restoration of the displacement on some of the known normal faults (O. Høltedahl, 1950; H. Høltedahl, 1958) will further close the gaps now occupied by the continental shelves and increase the degree of credibility of some geological correlations.

One further reservation must be made about the method of reconstruction, and that concerns the distortion inherent in the map projection used (conical projection, from Hilgenberg, 1966). This distortion is, of course, unavoidable and it should therefore be remembered that Figs. 37-40 can only portray the general pattern of what is taking place and that great detail is not obtainable.

A) Stage I Extending Rift (Fig. 37)

A tension rift, presumably related to thermal activity in the mantle, probably began to work a sinuous path northwards sometime in the Mesozoic era. The course of the rift was mainly dictated by the developing mantle convection cell, but the actual detail of the crustal rupturing must have depended on local inhomogeneities in the crust. If the dykes reported by Larsen and Møller (1968) in southwest Greenland are the first manifestation of this thermal activity in the area under consideration, then this structure at the southern end must be as old as middle Jurassic.

Fig. 37. Model for the Opening of Baffin Bay-Labrador Sea: Stage I.

Fig. 38. Model for the Opening of Baffin Bay-Labrador Sea: Stage II.

Fig. 39. Model for the Opening of Baffin Bay-Labrador Sea: Stage III.

Fig. 40. Model for the Opening of Baffin Bay-Labrador Sea: Stage IV.

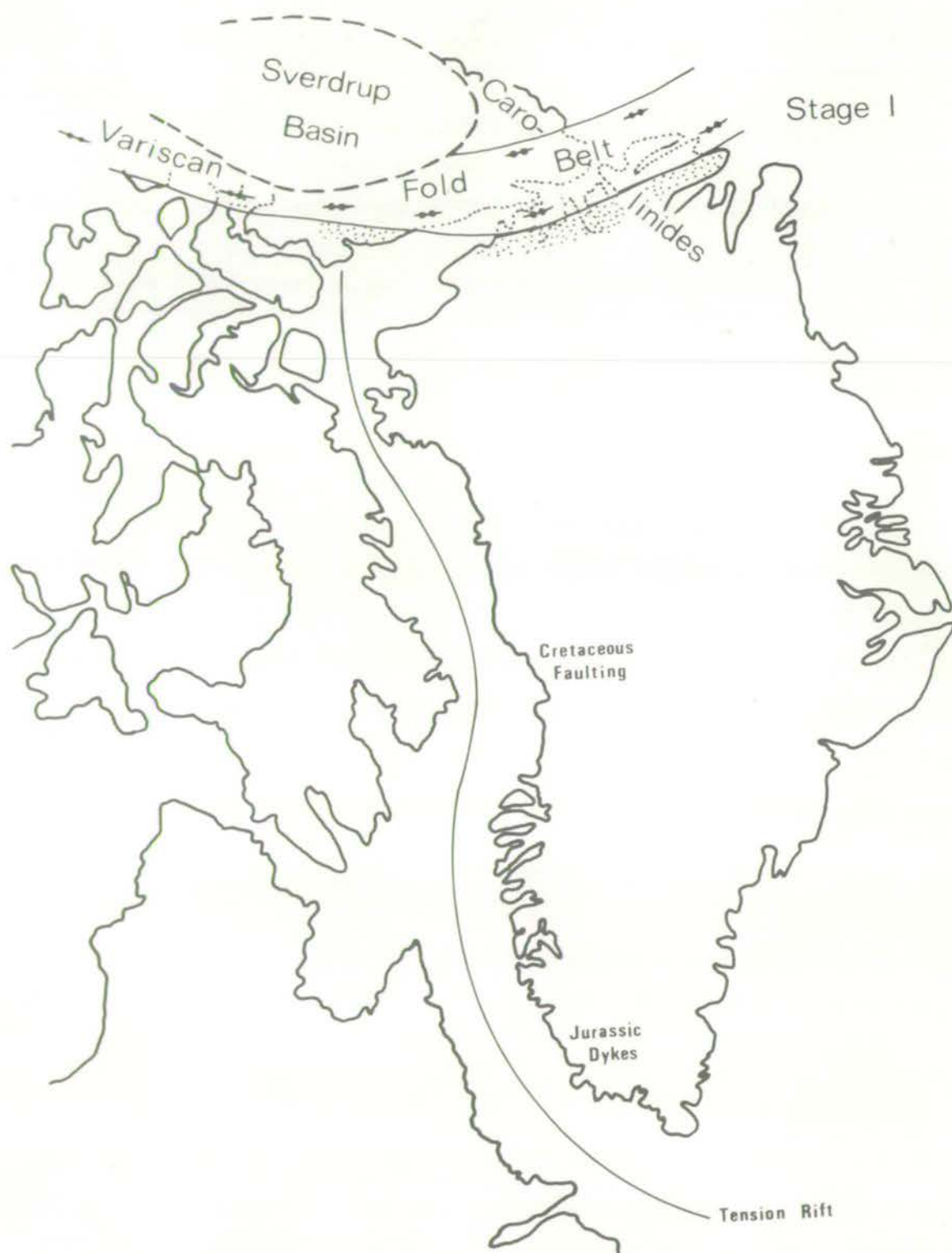


FIG. 37

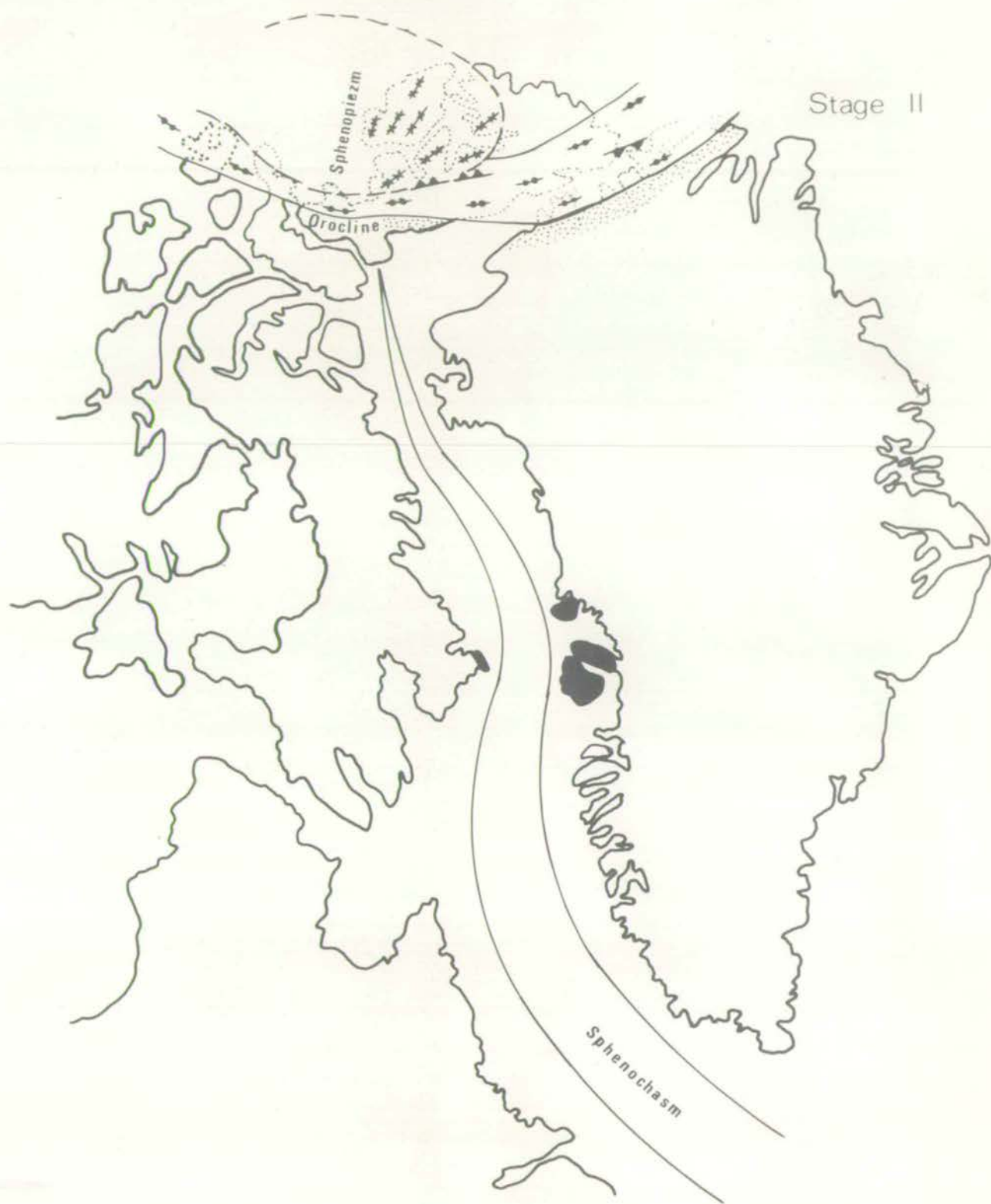


FIG. 38

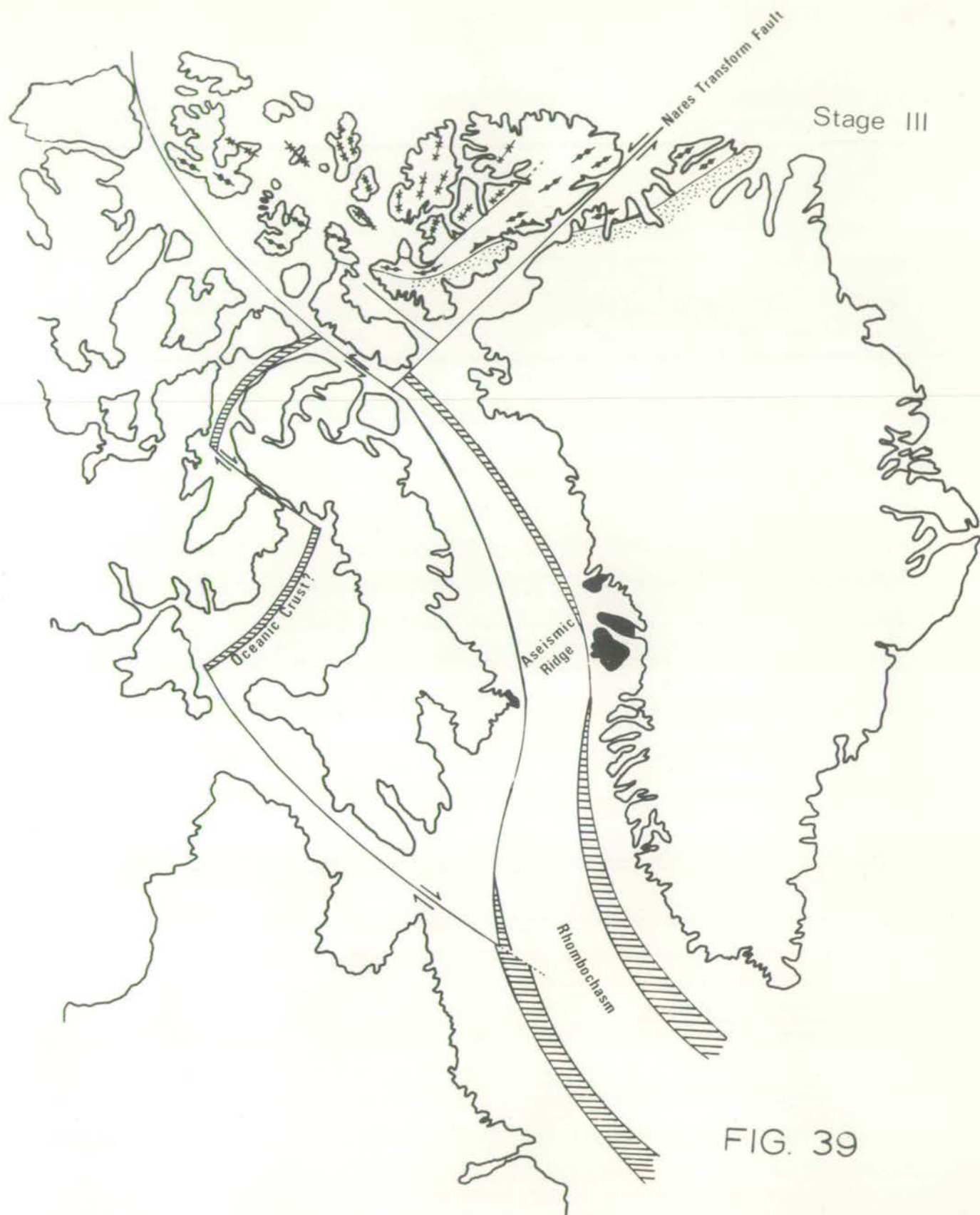


FIG. 39

Stage IV

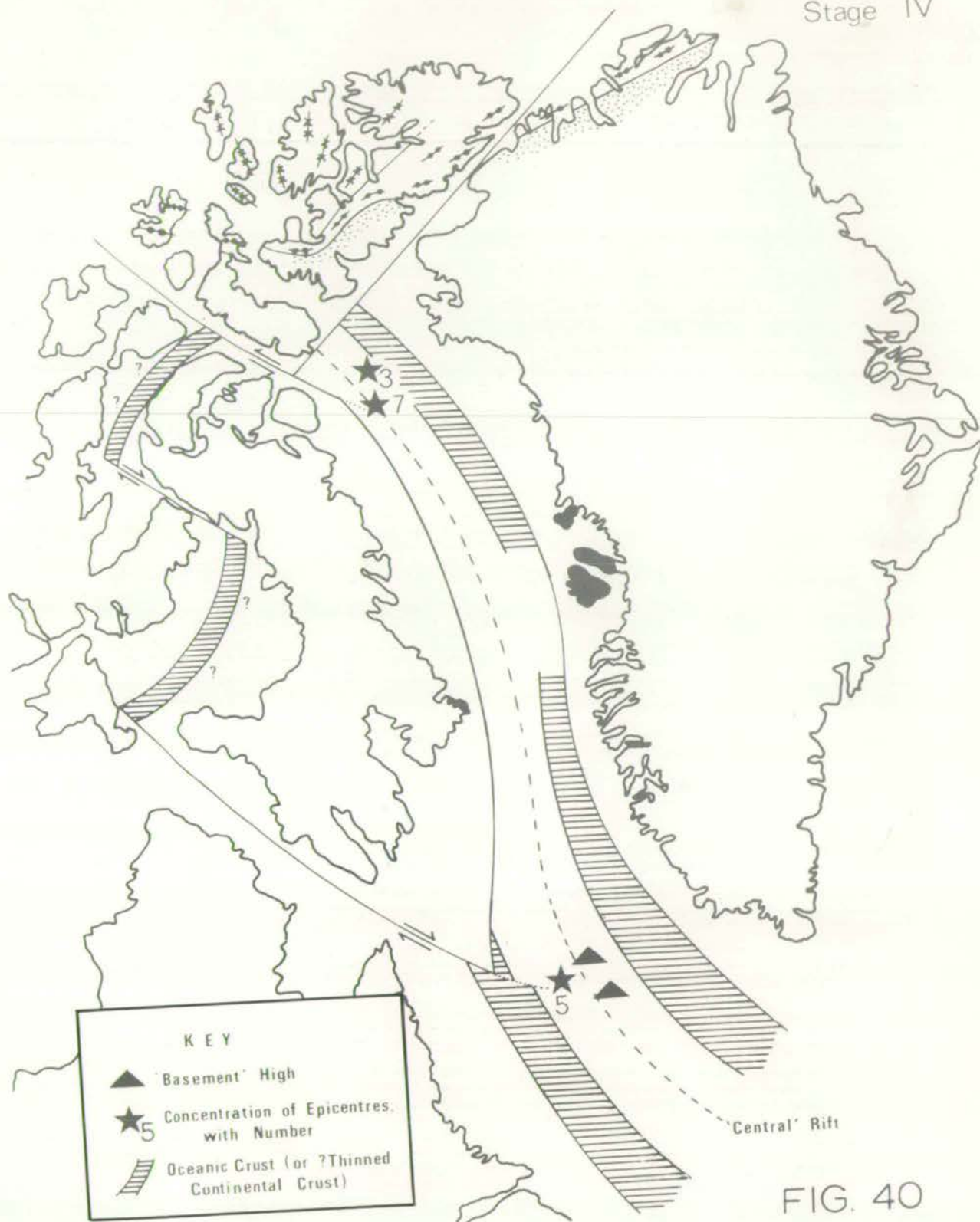


FIG. 40

The next tectonic activity recorded along these coasts is farther north in the Svartenhuk-Nugssuak area, where a prolonged episode of normal faulting began in the early Upper Cretaceous (Rosenkrantz and Pulvertaft, in press). Finally, the rift appears to have reached the southeast corner of Ellesmere Island by the early Tertiary, judging from the age of various structures there. However, when the advancing rift reached this point it encountered, nearly at right angles, a relatively young, thick, folded sequence in the form of the Franklinian geosyncline. This structure was in turn reinforced on its northern side with a thickness upwards of 10 km. of sediments comprising the Sverdrup basin. Apparently, the rift was unable to penetrate the greatly thickened crust in this region and instead terminated at that point, and a phase of simple rotation began, using the southeast corner of Ellesmere Island as a fulcrum or pivot.

B) Stage II Rotation, Folding and Volcanism (Fig. 38)

The wedge-shaped opening which developed between Canada and Greenland as rotation continued fits the definition of a sphenochasm as described by Carey (1958). Presumably the vicinity of Davis Strait was one area of very high heat flow and the voluminous outpouring of lava occurred in response. That the thermal activity in the mantle did persevere in a northwesterly direction is evidenced by the Upper Cretaceous-Tertiary basic intrusions and volcanics in the Sverdrup basin (Blackadar, 1964). He states that "by far the greatest concentration of basic plutons is in western Axel Heiberg Island and in structural highs on Cornwall Island and the Ringnes Islands", i.e. on strike with the course of the rift.

The rotation, pivoted in southeast Ellesmere Island, threw into compression that region to the northwest of the pivot. Three major effects are noted:

- 1) the originally nearly linear Franklinian fold belt began to bend into a broad U-shape, here named the Ellesmere orocline
- 2) the soft sediments filling the Sverdrup basin were subjected to compression, directed mainly from the east by the rotation of Greenland, resulting in a fan-shaped arrangement of fold axes, here named the Sverdrup sphenopiezms; Tozer and Thorsteinsson (1964) have drawn attention to the curious fact that the strike of the fold axes in the Sverdrup basin is transverse to the axis of the sedimentary synclinorium
- 3) in the region of Grinnell Peninsula on Devon Island and the east coast of Ellesmere Island, the incompetent Sverdrup sediments were thrust onto the Variscan fold belt; if the debatable thrusting in north Greenland is truly of Tertiary age (Ellitsgaard-Rasmussen, 1955; Haller and Kulp, 1962; Dawes, 1966), then the reversed sense of the thrusting, i.e. northwards, may be due to the yielding of the most incompetent member, this time the Variscan fold belt, resulting in the overturning towards the foreland of the north Ellesmere Island Carolinian fold belt

This phase of rotation continued until the bend of 50° currently displayed by the Ellesmere orocline was established.

G) Stage III Faulting and Translation (Fig. 39)

As the folding became tighter in the Sverdrup sphenopiezms, a transform fault (Wilson, 1966a) with left-lateral strike slip movement, here named the Nares transform fault, broke through the former warp in the Variscan fold belt near Bache Peninsula and extended across to the mid-Atlantic rift system. According to Carey's (1958) terminology, the Baffin sphenochasm is now more properly called a rhombochasm. From the period of this conversion the move-

ment of Greenland became entirely one of translation along the Nares transform fault. The folding of the Sverdrup sphenopiezum terminated at this time of breakthrough.

The newly introduced lateral movement of Greenland exerted a drag on Ellesmere Island, thereby partially releasing the compression at the orocline. This allowed the opening of extension faults in southern Ellesmere Island (Kerr, 1968), Jones Sound between Ellesmere and Devon Islands (Gregory et al., 1960, 1961) and Lancaster Sound between Devon and Baffin Islands (Thorsteinsson and Tozer, 1960; Gregory et al., 1961; Fortier et al., 1963; Barrett, 1966). The formation of Prince Regent Inlet and Foxe Basin probably also belongs to this period of extension faulting and must involve crustal thinning, if not the production of new oceanic crust. Fortier (in Fortier et al., 1963) states that "Parry Channel, which apparently marks a line along which beds and structures on one side are offset from those on opposite sides, and Prince Regent Inlet, which has a remarkably straight western shore, are probably the loci of faults but this is not demonstrable". Coupled with the opening of Prince Regent Inlet and Foxe Basin, some transcurrent movement along Lancaster Sound, Fury and Hecla Strait and Hudson Strait must have taken place. Evidence to support this conclusion includes the following: (i) there is an apparent left-lateral offset of the Brodeur-Devon homocline (Fortier et al., 1963, Fig. 1; Barrett, 1966) between Baffin and Devon Islands and also of the magnetic anomaly associated with the Boothia Arch (Gregory et al., 1961, Fig. 2); (ii) Heywood (1967) showed some east-west trending faults of unknown age in Melville Peninsula which may have facilitated or been the result of movement in Fury and Hecla Strait; and (iii) Hudson Strait was considered as a fault by Taylor (1910), and recently Hood and Bower (1966) produced magnetic evidence to show at least a component of southern downdropping.

Also indicated in Fig. 39 are the areas of new oceanic crust (in the Labrador Sea on either side of the ridge and in Baffin Bay on one side only) created as a result of the inferred sluggish movement of Baffin Island away from the ridge. The Davis aseismic ridge, developed in the same manner as the Wyville-Thomson ridge in the North Atlantic or the Walvis ridge in the South Atlantic, has also been indicated.

D) Stage IV Residual Activity (Fig. 40)

During part of the Tertiary, the widening of the Baffin rhombochasm was accomplished by movement along the Nares transform fault. However, the condition was eventually reached in which Greenland went into equilibrium between the opposed forces opening Baffin Bay on the west and the North Atlantic on the east. The greater structure appears to have prevailed and Greenland is now drifting away from the mid-Atlantic ridge at much the same rate as continental North America. The relatively weak seismic activity of the Labrador Sea ridge suggests that this is probably true, and it therefore follows that there would be little or no further movement along the Nares transform fault. This is confirmed by the striking lack of earthquake activity in that channel. Stress release associated with the minor seismic disturbances on the Baffin Bay structure is probably accommodated in the various straits and channels to the west, which are similarly characterized by a few epicentres.

The extrapolated lineaments of Lancaster Sound and Hudson Strait intersect the Baffin-Labrador ridge in the vicinity of the two major concentrations of epicentres in Baffin Bay and the Labrador Sea respectively. It is suggested that these concentrations of epicentres represent the points on the ridge where differential, i.e. slower, movement of Baffin Island relative to all other blocks was initiated. Why Baffin Island has lagged behind is not clear but structural evidence already discussed suggests that it has done so.

E) Remarks on the Model

Studies dealing with continental drift tend to fall into two distinct categories. The first type of presentation is conceived on a global scale and, liberally accompanied by sketch diagrams (e.g. Le Pichon, 1968), attempts to explain all the major structural phenomena of the earth's crust. Of necessity, this manner of approach is always lacking in detail. The second type of presentation is concerned with the examination of a restricted area, from which broad, general conclusions are often drawn (e.g. Kerr, 1967b). Clearly neither approach is scientifically sound, but if a comprehensive, detailed picture is ever to emerge then the second type is preferable to the first. As further geographical areas of manageable proportions are "solved" internally, then a consistent mosaic may someday be compiled.

The present study belongs to the second category, being expanded from one small volcanic province to embrace the natural geographical unit of Greenland and the Arctic archipelago. A reasonably consistent model has been proposed for the formation of all the principal geological features observed, but immediately beyond these arbitrary boundaries many problems arise. It should be stated in advance that a large proportion of the difficulties that arise are due to the scarcity of reliable information, notably in the Arctic Ocean basin where most of the major structures are imperfectly understood. Indicative of this lack of knowledge is the fact that the Lomonosov ridge has received such a wide variety of interpretations. These include a "nematath" (Carey, 1958), folded mountains related to the Eureka Sound fold belt and the Verkhoyansk Mountains of Siberia (Pushcharovskiy, 1960; Dibner et al., 1965), a volcanic structure based on magnetic susceptibility (King et al., 1966) and dredgings (Hakkel', 1958), and simply a boundary between ocean basins of differing ages (Wilson, 1966b). Needless to say, objections can be raised to each of these interpretations.

There is a somewhat better measure of agreement concerning the Alpha rise, which has both the topographic and magnetic expression of a block faulted area (Hunkins, 1961; King et al., 1966), with the implication of crustal extension. If this interpretation is correct and the present drift model is to be retained, then the rotation of Greenland and Ellesmere Island into the Arctic basin must be of a different age from the formation of the Alpha rise. Wilson (pers. comm.) believes that the compressive force which deformed the Franklinian geosyncline in Variscan times was directed from the northwest by the closing of a former Arctic ocean. That ocean is then supposed to have reopened in Pennsylvanian times into a narrow sea susceptible to periodic restriction of water flow and subsequent formation of the evaporites now observed at the base of the section in the Sverdrup basin. Aeromagnetic evidence (King et al., 1964) implies that a large part of the Arctic Ocean basin on the Canadian side of the Lomonosov ridge consists of foundered continental crust. If this is true then serious isostatic problems are raised. In the light of unsolved problems such as these it was considered unwise to try to incorporate the features of the Arctic Ocean basin into the present model.

Another problem concerns the fault in Lancaster Sound. Barrett (1966) interpreted the magnetic anomalies in such a way as to yield a fault plane dipping south at 45° . If this is true then the proposed transcurrent movement along this channel may have taken place along an older, nearly vertical fault plane. When the region was thrown into tension by the dragging away of Ellesmere Island, the normal fault was guided by the surface trace of the older transcurrent one but developed a new dip to the south.

In the Baffin Bay volcanic province there is an apparent inconsistency between the model and the conclusions of Rosenkrantz et al. (1942), who envisioned an extension of the Cretaceous seas southward from the Sverdrup basin.

Apart from the Coloradoan affinities of the early fauna, there is no other evidence that a sea opened up in this manner and, in fact, Tozer and Thorsteinsson (1964, Fig. 20) definitely favour a northward extension of the proto-Atlantic through the Labrador Sea and Baffin Bay. The model's mechanism of progressive tectonic activity northwards agrees palaeogeographically with Tozer and Thorsteinsson (1964) but still does not necessarily preclude a superficial overflow of the Sverdrup sea from first reaching Svartenhuk and Nugsuak if palaeontological considerations so demand.

Further to the south there is also the problem of bifurcation where the Labrador Sea ridge is supposed to meet the mid-Atlantic ridge. Although the mid-Atlantic ridge may now be the stabilized locus of production of new oceanic crust, the period of dual activity(?) of these ridges, or of the conversion of Greenland to a stagnant block, must have been extremely complex. Precise dates of activity are not available in order to allow construction of a model; therefore, this problem is directed to future investigators when more information is forthcoming.

Most of the objections to the present model stem from the relative newness of geological and geophysical investigations in the Arctic, and will probably be resolved as new data become available. Even so, there are strong similarities between this model and the composite picture presented by Matthews (1966), Laughton (1966), Girdler (1966) and Freund (1965), concerning the intersection of an oceanic ridge structure (Carlsberg) with a continental landmass (Afro-Asian block), to produce a sphenochasm (Gulf of Aden and the Red Sea) plus rotation and translation of one of the blocks (Arabian Peninsula). This analogy is continued in that both areas display a constriction in the sphenochasm at a point where the axis of the sphenochasm has either been offset or warped, and both of the narrows (Straits of Bab el Mandeb and Davis

Strait) are characterized by copious outpourings of lava. The development of "hot spots" on mid-oceanic ridge structures is not exceptional (e.g. Iceland, Azores, Bouvet, St. Paul-Amsterdam Islands) and may have no significance beyond representing local areas where mantle melting has been more extensive or where magma release was perhaps facilitated by the change in strike of the ridge. It is interesting to speculate that the Baffin Bay "hot spot" may be the relict early Tertiary equivalent of the present-day "hot spot" in the same latitudes, namely, Iceland.

If the analogy with the opening of the Red Sea is appropriate, then geophysical results from that area should allow predictions to be made about the Baffin Bay area. For instance, there should be a positive Bouguer gravity anomaly over the axis of the ridge, and deep seismic refraction profiles should confirm the sort of crustal layering characteristic of mid-oceanic ridges. Also, palaeomagnetic work on the Tertiary lavas should show rotation of Greenland relative to North America by an amount equal to the degree of bending effected in the Franklinian fold belt. Finally, the residual seismic activity suggests that detection of higher heat flow, associated with the ridge, may still be possible.

Answers to the objections and testing of the predictions will take considerable time. The geographical areas are immense and difficult of access; as a result, it may be decades before proper investigation, interpretation and debate resolve the current geological and structural enigmas.

In this summary the major topics of the previous chapters are brought together, and listed under each topic are the pertinent facts, arguments and hypotheses. The chapter concludes with a concise re-statement of the envisaged petrogenetic scheme and an evaluation of the sum total of the foregoing evidence.

I. The Lavas

- 1) the picritic and olivine basalts generally form thin flows, suggesting a highly fluid magma
- 2) the four principal zones in any flow are (a) basal chill, (b) lower massive zone, (c) upper vesicular zone and (d) chilled top
- 3) presence of dykes of appropriate composition and absence of any central eruption features suggest eruption principally through fissures
- 4) most eruptions of olivine-rich basalt were local phenomena, thereby making correlation of measured sections quite impossible
- 5) the basal breccias have a subaqueous, possibly submarine, origin judging from the type of alteration, and the attitude of the giant cross-bedding in the breccia units may be used to locate the source area
- 6) thick olivine basalt flows develop intra-flow differentiates, and at Cape Dyer the extremes of composition in one flow bracket all other compositions in the entire province
- 7) the feldspar-phyric basalts are generally thicker and cover larger areas than the picrite basalts, and are only found on the west Greenland side of Baffin Bay
- 8) eruptive history: picritic breccias - subaerial picrites - olivine basalts - feldspar-phyric breccias and/or flows - trachytes - carbonatites(?)

II. Chemical Characteristics of the Basalts

- 1) all but 2 of the 79 basalts analyzed are hypersthene-normative and are therefore referred to as tholeiitic (after Yoder and Tilley, 1962)
- 2) the olivine basalts are characterized by high MgO , Cr_2O_3 and NiO ; also low TiO_2 , K_2O , P_2O_5 , Ba, Sr, Rb, Y, Ga and Zr (the incompatible elements)
- 3) incompatible elements are enriched in the Svartenhuk olivine basalts over those of Baffin Island by a factor of approximately 1.5
- 4) trace element trends are continuous from olivine basalts to feldspar-phyric basalts
- 5) against MgO as an index of low-pressure fractionation, the rate of increase of incompatible elements in the feldspar-phyric basalts is greater than in the olivine basalts

III. Evidence Suggesting the (Polybaric) Fractionation of Olivine to Vary Bulk Compositions

- 1) a general decrease in modal olivine occurs from early picrites to late feldspar-phyric basalts
- 2) strong gravitative settling of olivine in thick olivine basalt flows and the rate of change in concentration of incompatible elements and Ni confirm that olivine is the principal fractionating phase
- 3) a plot of MgO against other oxides (after Powers, 1955) indicates olivine removal as being responsible for linear trends produced and limits the fayalite content of olivines
- 4) correlation coefficients in 21 x 24 matrices are strongly positive between MgO , Cr_2O_3 and NiO and strongly negative between MgO and the incompatible minor and trace elements
- 5) strong olivine control lines produced in the simple normative basalt tetra-

hedron and examination of concentrations of incompatible elements and nickel along these lines indicate olivine fractionation

- 6) strong olivine control lines exist in the modified CMAS tetrahedron
- 7) bulk composition of Group II magmas indicates that they must precipitate olivine en route to the surface, i.e. in a decreasing pressure field
- 8) presence of at least some euhedral (as opposed to skeletal) olivines in the one-phenocryst basalts indicates that the ascending magma probably did not reach the surface in 100% liquid condition

IV. Evidence Suggesting High Pressure Eclogite Fractionation to Vary Minor Element Compositions

- 1) incompatible elements are enriched by a factor of 1.5 in Svartenhuk olivine basalts without a corresponding difference in major element chemistry or nickel and chromium contents
- 2) the offsetting of trends occurs in certain of the simple variation diagrams, whereas others are perfectly linear
- 3) average of Svartenhuk olivine basalts has higher CaO/MgO , Ni/Mg and lower $\text{Na}_2\text{O/K}_2\text{O}$ ratios than Baffin Island average
- 4) principal component analysis demonstrates mathematical feasibility of eclogite fractionation to produce observed differences between the two suites
- 5) considering the bulk compositions, the model of magma production at 30 kb. provides a reasonable environment in which partial melting and eclogite fractionation can take place

V. Statistical Treatment

- 1) correlation coefficients lend support to the idea of olivine fractionation as a major control of variance of bulk compositions

- 2) discriminant function analysis rejects the null hypothesis, i.e. that average Baffin Island olivine basalt equals average Svartenhuk olivine basalt, and in so doing provides a mathematical function to categorize analyses of basalts from the Baffin Bay region
- 3) principal components analysis supports eclogite fractionation

VI. Models Presented

- 1) a model of the opening of Baffin Bay is based only on field relations observed by the author
- 2) three petrogenetic models attempt to satisfy the peculiarities of both bulk chemical composition (low incompatible elements) and phase relations (non-attainment of equilibrium at low pressure):
 - (a) generation at 20 kb. fails because it requires a mantle composition unlike average garnet peridotite and does not provide a favourable environment for eclogite fractionation
 - (b) generation at 30 kb. provides both a high degree of partial melting to produce a hypersthene-normative primary magma and an opportunity for fractionation of eclogite
 - (c) generation at 40 kb. shows that the projected bulk compositions do not conform with known phase relations
- 3) a four-stage model for the opening of the Labrador Sea, Baffin Bay, Nares Strait, Hudson Strait, Lancaster Sound, etc., is based mainly on published geological and geophysical work including palaeontology, palaeomagnetic studies, seismic refraction profiles, seismicity, aeromagnetic surveys, jigsaw fits and, in particular, structural relations in the vicinity of Nares Strait, including folding and normal, thrust and transcurrent (transform) faulting

VII. Correlation between the Cape Dyer Region of Baffin Island and Svartenhuk Peninsula

- 1) basement rocks exhibit a similar grade of metamorphism (garnet amphibolite facies with a possible increase to granulite facies northwards) and similar rock types, especially the garnetiferous gneisses and tourmaline-bearing quartzo-feldspathic dykes
- 2) that there are Phanerozoic rocks at all along the shores of Baffin Bay is worthy of note, and that they should be diametrically disposed and of the same geological age (late Cretaceous-early Tertiary) is even more remarkable
- 3) evidence exists in both provinces for normal faulting contemporaneous with deposition of late Cretaceous-early Tertiary sediments
- 4) there is a similarity of rock types and fossil flora content in the sediments from both sides
- 5) there is a similar period of eruption of lava with radiometric ages in the range 58-54 my. ago
- 6) "offshore" source region is demanded for both basalt provinces; i.e. a common source region could lie between the two areas as now exposed
- 7) formation of basalt breccias with giant cross-bedding is common to both areas
- 8) similar magma-types are erupted, i.e. a hypersthene-normative picrite basalt with low incompatible elements
- 9) trace elements plot on smooth trends from Baffin Island picrites through Svartenhuk picrites and olivine basalts to feldspar-phyric basalts
- 10) similar dykes of carbonate-rich material are common to both areas

VIII. Re-statement of Petrogenetic Scheme

Generation of the basalt magmas, now represented by lava flows of Tertiary age along the coasts of Baffin Bay, is believed to be the product of a partial melting event in the mantle at a pressure of approximately 30 kb. This pressure was chosen because the position of its pseudo-invariant point in the CMAS system coincided with the bulk compositions believed to be parental in both basalt provinces. (The method of selecting the parental compositions was initially one of a process of elimination, but the decision was confirmed by petrographic and stratigraphic considerations.) At the conclusion of partial melting, a small portion of the primary magma was erupted directly to the surface, the composition of the liquid never leaving the primary phase volume of olivine, and this material is now considered to be represented by the picrite basalts of Baffin Island.

The remainder of the partial melt, retained at high pressure, suffered approximately 33% of eclogite fractionation. This resulted in the raising of the levels of the incompatible elements by a factor of 1.5 over the Baffin Island parental average without at the same time greatly changing the major element bulk composition. This evolved magma was then erupted in precisely the same condition of polybaric fractionation of olivine as that experienced earlier by the Baffin Island parental magma, and is now represented as the parental composition of Svartenhuk. Whereas the Baffin Island basalt magma source appears to have been practically exhausted in the early stages, the greater volume of magma in Svartenhuk underwent prolonged gabbro(?) fractionation at pressures less than 10 kb., thereby generating the feldspar-phyric basalts with their late-stage exponential increases in incompatible elements. On present evidence there is no reason to believe that the trachytes are anything but high-level fractionates of the feldspar-phyric basalts. The

injection of comparable carbonate-rich materials in both provinces may represent the last residua of material which fractionated to carbonatite-like compositions at 30 kb. before being erupted.

The above model is consistent with petrographic and chemical data collected in the course of this research and is in agreement with what is currently accepted concerning the phase relations of basalt magmas both at high and low pressures.

IX. Conclusion

From the high degree of stratigraphic and geochemical correlation between the two basalt provinces, and from the weight of other geological and geophysical evidence in the eastern Arctic, the conclusion may be drawn that the two provinces are the fragments of one formerly continuous basalt "plateau", now separated by continental drift. Such being the case, the production of magma and rifting of the continents are simply two manifestations of one major geological event and are therefore inseparable either in time or in space.

APPENDIX APETROGRAPHYI. Introduction

The purpose of this appendix is to provide general petrographic information to accompany the chemical analyses. The approach will be to describe the petrography of the minerals, followed by short petrographic descriptions of each analyzed specimen. In the latter section, locality is noted, phenocryst assemblage is presented under the sample number (if discernible), general texture is described, and an estimated mode with mineral compositions (where determined) is included. Samples AA-63, C-56, DX-52, E-2, G(d)-2, 512, 589, 629, 641 and 658 were point-counted. The determination of olivine compositions was done by X-ray diffraction, using the method of Yoder and Sahama (1957), modified by using NaCl as the reference standard. Plagioclase compositions were determined by the Michel-Levy symmetrical extinction angle method on polysynthetic albite twinning in the zone perpendicular to (010), using Tobi's (1961) high-temperature curves.

For the purposes of this petrographic study it is convenient, in order to prevent unnecessary duplication, to discuss the rocks as a single group rather than as suites from two provinces. Where there are differences between the Baffin Island and Svartenhuk suites, these are indicated. Also, in many instances the phenocrysts, olivine in particular but sometimes plagioclase as well, have been described as skeletal in form. There is no difficulty in recognizing these grains as partially formed crystals rather than as possible resorbed phenocrysts. In every case the edges of the crystals (seen as corners in section) are perfectly sharp, and the large embayments occur in the faces. If resorption into the liquid were responsible for the habits developed, the free energy considerations would demand that corrosion should take place on

the corners and edges first, but this is not observed in the early basalts. This conclusion is in complete agreement with the work of Drever and Johnston (1957) on olivines from similar rocks on Ubekendt Island, west Greenland, and of Kopecky and Voldan (1959) on some experimentally investigated rocks.

One of the more interesting features of these basalts is that they have crystallized only one variety of pyroxene, namely, clinopyroxene. Vaasjoki (1965) has reported orthopyroxene in a basalt from Asuk, Disko Island, but its intimate association with native iron suggests that it is also a product of the unusual reducing conditions which must have prevailed. This absence of orthopyroxene holds true, not only for the extremely olivine-rich members under study (where olivine and liquid seem to have reacted to produce clinopyroxene; see Hytonen and Schairer (1961) and O'Hara (1968)), but also for the entire sequence of differentiation to quartz-normative tholeiites. As may be seen from Figs. 21-23 the bulk composition of the lavas being so close to the normative divide renders the crystallization of orthopyroxene an unlikely event, although had there been differentiates in the intermediate range, hypersthene might have appeared.

The order of appearance of phases in the Svartenhuk suite has already been portrayed in Fig. 34. In Baffin Island all the breccias are characterized by phenocrysts of olivine and microphenocrysts or microlites of plagioclase. It is therefore possible that many of the subaerial flows may also have contained plagioclase as a second phenocryst phase, but this is rarely demonstrable. However, it is also possible that the initial eruptions (the breccias) suffered more extensive cooling en route to the surface, whereas later flows passing through the pre-heated conduit did not cool sufficiently to allow the formation of a second phenocryst phase. In both provinces chromian spinel is an early phenocryst and it will be discussed later.

One final topic before the mineralogy is discussed concerns the nomenclature of the rocks. The name "picrite" has been reserved for basalts containing

more than 25% modal olivine. Otherwise the rocks are referred to as olivine basalts, except for those in which plagioclase is the principal phenocryst phase. These feldspar-phyric basalts occur only rarely without olivine, clinopyroxene and magnetite as coexisting phases, although the olivine is usually completely pseudomorphed.

II. Olivine

Where olivine compositions have been determined, the fayalite content is given in the individual petrographic description. In general, the range is from Fa_8 to Fa_{21} , these values being $\pm 1\%$ Fa . The size ranges from infinitesimally small microlites in the basaltic glasses to phenocrysts having a maximum dimension somewhat in excess of 1 cm. in some of the thick cumulitic flows. The largest olivines in the parental Group II compositions of Chapter 4 do not have maximum dimensions in excess of 4 mm.; average maximum dimension for 16 of these compositions was 2.2 mm. and average dimension was less than 1 mm. Therefore, the high MgO in these basalts may be attributed, in part, to a profusion of small olivines rather than a few large crystals.

The shape of the olivines varies widely from microlites and bizarre skeletal varieties to subhedral and perfectly euhedral crystals, and the habit appears to be largely determined by the rate of cooling.

The principal types of alteration are partial conversion to iddingsite and partial or complete conversion to serpentine. In the olivines of some leucocratic segregations in thick flows, several concentric rings of iddingsite and olivine are built up in a single crystal. This is a possible reflection of cycles of periodic concentration and eventual loss of volatiles in the differentiating magma (Edwards, 1938). In at least one flow (I-102) it may be seen that iddingsitization is later than poikilitic enclosure of some of the

olivines in the clinopyroxene, as those enclosed are not altered. Also, the olivines of the breccias are not characterized by any alteration to iddingsite. In some tuffs on Baffin Island and in some of the feldspar-phyric basalts of Svartenhuk, olivine has been pseudomorphed by carbonate.

III. Chrome Spinel (Picotite)

The abundant, tiny chrome spinels with maximum dimensions of 0.02 mm. are most frequently enclosed in the olivine phenocrysts, although individual grains are occasionally found in a fine-grained groundmass or basaltic glass. Vaasjoki (1965) has reported a partial analysis and results of X-ray diffraction work on the reddish spinels, which place them in the range of chromiferous spinel-hercynite or, more simply, picotite.

The range of stability of picotite in chrome-bearing picritic liquids is not known. In the petrogenetic model (Chapter 4) it was proposed that olivine began its crystallization at depth and continued to the surface. If the central inclusions of idiomorphic picotite in olivine have petrogenetic significance, then it is possible that they are intermediate- to high-pressure relicts upon which the olivine crystals nucleated. This can only be true if the picotites have a large pressure range of stability, since their occurrence as euhedral grains in some groundmasses might demonstrate stability at atmospheric pressure.

IV. Plagioclase

A few plagioclase compositions are included in the individual petrographic descriptions. In general, the plagioclase laths are small, zoned and without good polysynthetic twinning, making determination of composition exceedingly difficult. In general, the plagioclases lie in the range An50-65, perhaps

surprisingly albitic for such primitive basalts, although the fact that the single pyroxene is augite must account for a large proportion of the calcium. The plagioclases of the feldspar-phyric basalts are generally characterized by oscillatory zoning.

Laths of plagioclase range in size from microlites in the glasses up to crystals approximately 2 cm. in length in the leucocratic segregation veins of thick flows. Occasionally in the glasses, equant, rhomboidal, rather quenched-looking plagioclases occur.

In general, the plagioclase is very fresh, although in some of the Svartenhuk picrites, especially those of Group I, they are strongly altered to zeolite. It is not believed that any large chemical changes have accompanied this alteration, as the altered specimens are not noticeably off-trend in the variation diagrams. The only occurrence of plagioclase alteration in the Baffin suite is sericitization(?) in the palagonite (where the olivine remains remarkably fresh) and replacement by carbonate in some tuffs (not analyzed).

V. Augite

As mentioned earlier, the only pyroxene is a relatively high calcium variety. This much has been deduced about the chemical composition as the result of optical work done by the author (Clarke, 1965, unpub.), wherein the $2V_x$ of pyroxenes in 5 flows in Baffin Island were found to be between $50-53\frac{1}{2}^\circ$. Similar optical work was done by Noe-Nygaard (1942), also establishing the high calcium nature of the pyroxenes in Svartenhuk. Optical work has also shown that there may be considerable chemical variation, especially amongst the pyroxenes of the feldspar-phyric basalts, which tend to be zoned and are probably titaniferous, as the purplish-brown colour would suggest.

Clinopyroxene is never found as a phenocryst on the Baffin side and is the last phase to appear as a phenocryst in the Svartenhuk suite. Therefore,

only rarely are the augites euhedral and their most frequent occurrence as phenocrysts is anhedral grains in glomerophyritic clusters with plagioclase. The textures developed by the augites range from poikilitic to ophitic or granular, depending very much on the individual composition. The cleavage is usually well developed, and twinning is most prominent in the leucocratic intra-flow differentiates and the feldspar-phyric basalts.

There is rarely any alteration to the clinopyroxenes. A possible exsolution of opaque material occurs in sample 629.

VI. Magnetite

For the sake of simplicity, the opaque phases in these rocks are collectively referred to as magnetite in the petrographic descriptions. An examination of the opaque minerals in reflected light has revealed that many complex relationships exist between the various spinels and oxide minerals. These relationships include the following:

- 1) skeletal magnetites in the sideromelane of the feldspar-phyric basalts
- 2) vermicular intergrowths of oxides and silicates
- 3) poikilitic inclusion of early-formed olivines by magnetite
- 4) occurrence of magnetite and ilmenite as discrete phases in the same rock
- 5) exsolution of ilmenite from magnetite
- 6) intergrowths between spinel and ilmenite in the groundmass (the spinel being of different composition from that enclosed in the olivine phenocrysts)
- 7) some spinels zoned outwards to magnetite
- 8) alteration products in the serpentinization of olivines
- 9) secondary oxidation and hydration of early-formed oxides to form hematite and goethite(?)

As demonstrated in Fig. 34, magnetite (probably titaniferous) was a sporadically occurring phenocryst in the early eruptives on Svartenhuk. In many of the later feldspar-phyric basalts, subhedral and euhedral magnetite phenocrysts coexist with skeletal magnetite or ilmenite in the groundmass. In addition, some of these later basalts contain specks of sulphide, and one or two may contain native copper.

VII. Sideromelane

Basaltic glass forms up to 80% of some of the samples analyzed. It is normally pale green in plane polarized light and perfectly isotropic. The rapid cooling has produced perlitic cracks, most of which are centred on prominent phenocrysts.

The weaker alteration product of sideromelane is termed palagonite (after Peacock and Fuller, 1928) and is characterized by an uptake of water which causes a colour change, although optical isotropy is retained. This colour change is from pale green to dark green in the black breccias or to reddish-brown in the orange breccias. The stronger alteration involves both physical and chemical attack on the sideromelane, presumably by superheated water, resulting in the formation of birefringent fibropalagonite (after Munck, 1942). The envelopes of fibropalagonite about the sideromelane and palagonite shards also may contain large quantities of zeolite and sometimes are accompanied by leached ferromanganiferous(?) globules (Bonatti and Nayudu, 1965; Bonatti, 1967). That the palagonite and fibropalagonite are strongly hydrated is suggested by samples RBB and ROB, which average 35-40% of these alteration products and $8.0\% \text{H}_2\text{O}^+$. On the assumption that the unaltered basaltic material in these specimens has the average value of about $1\% \text{H}_2\text{O}^+$, the palagonite and fibropalagonite contain on average about $18\% \text{H}_2\text{O}^+$.

VIII. Zeolites

The case for regarding at least some of the zeolites as magmatic in origin has already been discussed in Chapter 3. The occurrence of zeolites in the cavities of completely fresh lava flows on Baffin Island and in fresh sideromelane of both provinces favours this interpretation. Of course, there are also the picritic flows of Svartenhuk, in which most of the zeolites are obviously breakdown products of plagioclases.

As many as four different varieties of zeolite have been recognized in a single flow, two of which are analcite and phillipsite. However, no detailed work has been done.

IX. Apatite

Apatite has been detected in only two specimens, 629 and 670, both of which are coarse-grained relative to the other basalts. The apatite needles tend to radiate out from patches of fine-grained interstitial material, and the P_2O_5 in most specimens is therefore probably contained entirely in the fine-grained groundmass.

X. Myrmekite

A feature of the fine-grained interstitial material, found in the leucocratic segregations of thick flows, is the development of what appears to be a quartz-feldspar intergrowth. These leucocratic segregations represent the most differentiated material on Baffin Island, and since quartz is generated by the norm calculation, modal quartz is a distinct possibility.

XI. Chlorite

A chloritic mineral is seen to exist as pseudomorphs after olivine in

some of the feldspar-phyric flows; otherwise, it occurs mainly as interstitial patches and vesicle fillings.

XII. Petrographic Descriptions

A) Baffin Island

- A-5 Picritic portion of thick flow at radar station, Cape Dyer. Euhedral oliv and anhedral olivine (Fa_{19}) phenocrysts (cumulus) embedded in large poikilitic grains of plagioclase and less abundant augite. Olivines are slightly iddingsitized and contain nearly opaque, euhedral grains of spinel. Approx. mode: Oliv 50%, Plag 30%, Cpx 20%, Sp trace
- A-6 Leucocratic, olivine-poor portion of same flow as above. Olivines small, subhedral, slightly iddingsitized and without spinel inclusions. Ophitic texture between plagioclase and augite. Magnetite skeletal. Approx. mode: Oliv 10%, Plag 45%, Cpx 45%, Mt 1%
- AA-19 Same flow as above. Second leucocratic and vesicular band from the top and 1 m. thick. Coarse-grained aggregate of plagioclase and twinned augite, both of which are strongly zoned. Olivines small, rounded and partly iddingsitized. Interstitial material consists of skeletal magnetite, feathery augite and a wormy intergrowth of plagioclase and quartz(?) resembling a myrmekitic texture. (Plate V). Approx. mode: Oliv 1%, Plag 45%, Cpx 45%, Interstit 4%
- AA-26 Picritic portion of same flow, 2 m. below AA-19. Mainly subhedral oliv olivine phenocrysts (cumulus) poikilitically enclosed in large zoned plagioclase and augite (intercumulus). Olivines slightly iddingsitized and contain euhedral inclusions of spinel. Some skeletal magnetite

along the boundaries between the intercumulus and cumulus crystals.

Approx. mode: Oliv 50%, Plag 30%, Cpx 20%, Sp trace, Mt trace

AA-30 Same flow 1.5 m. below AA-26. Euhedral and subhedral olivine (Fa_{19})
oliv phenocrysts (cumulus) enclosed in large zoned poikilitic grains of plagioclase and augite (intercumulus). Olivines enclose the characteristic idiomorphic spinel and are partially iddingsitized. A zeolite forms part of the intercumulus material as well as filling the small vesicles. The olivines enclosed in Cpx are definitely anhedral, whereas those enclosed in Plag are euhedral, suggesting a possible reaction of the olivine with the liquid to form clinopyroxene. (Plate VI.) Approx. mode: Oliv 55%, Plag 20%, Cpx 20%, Zeol 15%, Sp trace

AA-63 Same flow as above, 7 m. below highest point exposed on the knoll, which in turn must represent nearly the top of the flow, judging from the thickness of the vesicular portion of the flow to this point. Strongly resorbed olivines with no spinel inclusions and all showing evidence of at least one episode of iddingsitization followed by a further period of olivine growth. Ophitic texture between plagioclase and clinopyroxene, both of which are zoned. Interstitial material consists of microlites of plagioclase and clinopyroxene, skeletal magnetite, iddingsite (hematite?) and a dusting of fine-grained magnetite. Approx. mode: Oliv 5%, Plag 45%, Cpx 45%, Interstit 5%

C-4a Upper spherulitic portion of subaerial flow 7 m. thick, Padloping
oliv Island. Subhedral and euhedral olivine phenocrysts with idiomorphic spinel inclusions in a groundmass of radiating feldspar and clinopyroxene microlites. Zeolites confined to small, irregular cavities

usually elongated parallel to the plagioclase microlites. (Plate VII.) Approx. mode: Oliv 50%, Gm 48%, Zeol 2%, Sp trace

- C-15 Subaerial flow 4 m. thick, Padloping Island. Anhedral to euhedral oliv olivine phenocrysts (cumulus) with spinel inclusions and only rare patchy alteration to iddingsite. Large crystals of plagioclase and smaller crystals of clinopyroxene poikilitically enclose the olivine phenocrysts. As in AA-30 the olivines tend to be corroded if enclosed by pyroxene. Approx. mode: Oliv 45%, Plag 30%, Cpx 25%
- C-25(b) Lower chilled margin of a 2 m. thick subaerial flow, Padloping Island. oliv + Anhedral to euhedral olivine phenocrysts with red spinels and very plag slight alteration of margins to iddingsite. One or two plagioclase phenocrysts. Groundmass consists of plagioclase laths, clinopyroxene microlites and magnetite. Approx. mode: Oliv 20%, Gm 80%
- C-56 Centre of a dyke 2 m. wide, Padloping Island. Phenocrysts of olivine, oliv + the larger ones partly serpentized, and an occasional phenocryst plag of plagioclase. Complete gradation in size between phenocryst and groundmass varieties of olivine and plagioclase. Ophitic texture between plagioclase and augite in groundmass. Approx. mode: Oliv 15%, Plag 40%, Cpx 40%, Mt 1%
- DX-9 Subaerial flow 7 m. thick, Padloping Island. Generally euhedral oliv olivine phenocrysts with spinel inclusions and about 50% alteration to iddingsite. Groundmass plagioclase laths enclosed in large poikilitic augite crystals. Approx. mode: Oliv + Idd 20%, Plag 40%, Cpx 40%, Mt 1%, Sp trace

- DX-18 Oliv + plag Chilled block from orange breccia, Padloping Island. Phenocrysts of olivine with spinel inclusions and phenocrysts of plagioclase in a glassy groundmass showing very fine magnetite and protomicroclitic crystals of clinopyroxene. Approx. mode: Oliv 15%, Flag 15%, Cpx 70%
- DX-24 Oliv Irregular subaerial flow 1-2 m. thick, Padloping Island. No thin section.
- DX-31 Oliv Subaerial flow 3 m. thick, Padloping Island. Subhedral to euhedral olivines (Fa_{15}) with spinel inclusions and jackets of iddingsite. Ophitic to poikilitic texture between plagioclase and augite. Approx. mode: Oliv 40%, Flag 30%, Cpx 30%, Mt 1%, Sp trace
- DX-48 Oliv Subaerial flow 4 m. thick, Padloping Island. As DX-31. Approx. mode: Oliv 25%, Flag 35%, Cpx 35%, Mt 2%, Sp trace
- DX-52 Oliv Subaerial flow 3 m. thick, Padloping Island. Large olivine phenocrysts (Fa_{10}) with abundant red spinels and slight alteration to iddingsite. Ophitic to poikilitic texture between plagioclase and augite. Approx. mode: Oliv 50%, Flag 25%, Cpx 25%, Mt 2%, Sp trace
- E-2 Oliv + plag Black breccia, Cape Searle. Fresh euhedral and skeletal olivine phenocrysts with spinel inclusions and also a few phenocrysts of plagioclase. Unaltered glass (sideromelane) is greenish and completely isotropic. Each fragment of glass has a complete darkened border of palagonite and individual fragments may be separated by a zone of fibropalagonite. Some vesicles are filled with a zeolite (chabazite?). (Plate VIII.) Approx. mode: Oliv 10%, Flag 5%, Siderom 35%, Palag 20%, Fbpalag 25%, Sp trace

- FD-11 Dyke 8 m. wide, Cape Searle Island. Serpentine pseudomorphs after
oliv + euhedral olivines, but included spinels are unaltered. Occasional
plag plagioclase phenocrysts. Doleritic texture in groundmass. Approx.
mode: Oliv 5%, Plag 50%, Cpx 45%, Mt 1%, Sp trace
- FF-41 Dyke margin, 3 m. wide, Cape Searle Island. Olivines subhedral to
oliv + euhedral with only minute alteration of a few phenocrysts to serpen-
plag tine. Spinel large and euhedral, some of which are found in the
groundmass rather than the olivines. Plagioclase phenocrysts usually
in monomineralic glomeroporphyritic clusters but occasionally
clustered with olivines as well. Fine-grained groundmass consists
of roughly equal proportions of plagioclase laths and clinopyroxene
microlites. Approx. mode: Oliv 15%, Plag 2%, Gm 80%, Sp trace
- G(b)-15 Subaerial flow 5 m. thick, Durban Island. Anhedral to euhedral
oliv olivine phenocrysts with spinels about half altered to iddingsite.
Ophitic texture in groundmass. Approx. mode: Oliv 25%, Plag 35%,
Cpx 35%, Mt 1%, Sp trace
- G(d)-2 Subaerial flow 15 m. thick, Durban Island. Olivines large with abun-
oliv dant opaque spinel inclusions. Augite greenish, large and poikilitic
towards olivine and plagioclase. Approx. mode: Oliv 40%, Plag 30%,
Cpx 30%, Mt 2%, Sp 1%
- G(d)-34 Sample from talus, Durban Island. No olivine. Large intergrown
crystals of augite and zoned plagioclase. Texture variable from
poikilitic plagioclase through ophitic to poikilitic augite. Much
skeletal magnetite. Also fine-grained interstitial patches of
microlitic augite, feathery plagioclase, fine-grained magnetite and
myrmekite(?). Approx. mode: Plag 45%, Cpx 45%, Mt 5%, Interstit 5%

- I-64 Oliv Basaltic block in orange breccia, Reid's Bay. Generally subhedral to euhedral fresh olivine phenocrysts (Fa_{14}) with some reddish spinels enclosed. Groundmass contains recognizable plagioclase laths, reddish spinels, microlites of augite, fine-grained magnetite and minor glass. (Plate IX.) Approx. mode: Oliv 35%, Plag 30%, Cpx 30%, Glass 2%, Mt 2%, Sp trace
- I-102 Oliv + plag(?) Subaerial flow 5 m. thick, Reid's Bay. Subhedral phenocrysts of olivine with inclusions of spinel and altered rims of iddingsite except where olivine has been poikilitically enclosed by clinopyroxene. Minor plagioclase phenocrysts. Ophitic texture in groundmass. Approx. mode: Oliv 25%, Plag 35%, Cpx 35%, Mt 2%, Sp 1%
- P-5 Oliv Subaerial flow, Cape Dyer. Skeletal to euhedral olivine phenocrysts with spinel inclusions and minor alterations to iddingsite. Both augite and plagioclase form large poikilitic crystals towards the earlier-formed olivine. Cavities are filled by two zeolites, analcite(?) and phillipsite(?). Approx. mode: Oliv 30%, Plag 30%, Cpx 25%, Zeol 10% Mt 2%, Sp trace
- PP-10 Oliv Subaerial flow (near top) about 30 m. thick, Cape Dyer. Large fresh olivine phenocrysts with opaque spinels. Ophitic texture in groundmass between plagioclase and augite. Approx. mode: Oliv 35%, Plag 35%, Cpx 30%, Mt 2%, Sp trace
- PP-18 Oliv Same flow as PP-10 but 18 m. lower. As above. Approx. mode: Oliv 55%, Plag 20%, Cpx 20%, Mt 1%, Sp trace
- R-13 Oliv Subaerial flow 14 m. thick near lower contact. Large generally euhedral phenocrysts of olivine with reddish spinel inclusions and

slight alteration to iddingsite. Ophitic texture in groundmass.

Approx. mode: Oliv 40%, Plag 30%, Cpx 30%, Mt 1%, Sp trace

- R-16 Segregation band in R-13 flow about 5 m. from base. Olivines strongly resorbed and iddingsitized. Both plagioclase and augite are strongly zoned and form an ophitic texture. Large skeletal magnetites associated with interstitial patches of fine-grained microlitic augite, feathery plagioclase and granular magnetite. Approx. mode: Oliv 5%, Plag 45%, Cpx 40%, Mt 5%, Interstit 5%
- RBB Black breccia. Olivine and plagioclase phenocrysts in perfectly isotropic sideromelane. Each sideromelane fragment is encased in a rim of palagonite and individual fragments are separated from each other by zeolites. Approx. mode: Oliv 15%, Plag 15%, Siderom 30%, Palag 25%, Zeol 5%
- oliv +
plag
- ROB Orange breccia. Phenocrysts of olivine, reddish spinel and plagioclase in isotropic sideromelane and extensive orange palagonite. Individual glass fragments separated by fibropalagonite, zeolite (chabazite?) and clots of reddish-brown opaque material. (Plates XI, XII.) Approx. mode: Oliv 10%, Plag 5%, Siderom 30%, Palag 35%, Fbpalag 15%, Zeol 5%, Opaque 2%
- oliv +
plag
- ROR Loose block. Subhedral olivines with spinel inclusions and only minor alteration to iddingsite. Two habits of magnetite(?) in groundmass, with euhedral variety being phenocrysts(?). Ophitic texture in groundmass, the augite sometimes being poikilitic towards the olivines. Approx. mode: Oliv 55%, Plag 25%, Cpx 20%, Mt 1%, Sp trace
- oliv +
mt(?)

- S-28 Loose block. Olivines (Fa_{21}) with reddish spinels and alteration
oliv of margins to iddingsite. Ophitic-poikilitic texture in groundmass.
Approx. mode: Oliv 35%, Plag 30%, Cpx 25%, Mt 2%, Sp trace
- SOG Orange breccia, Cape Searle. No thin section.
- T-42 Margin of dyke 1-2 m. wide, Cape Searle. Fresh euhedral pheno-
oliv + crysts of olivine with enclosed reddish spinels. Also a few pheno-
plag crysts of plagioclase often in aggregated clusters. Occasional
reddish spinel in groundmass. Matrix fine-grained with clinopyroxene
appearing as microlites. Approx. mode: Oliv 30%, Plag 5%, Gm 65%,
Sp trace
- T-47 Margin of dyke 2 m. wide, Cape Searle. Generally euhedral and
oliv + skeletal phenocrysts of olivine aligned parallel to margin of dyke.
plag Olivines characterized by small reddish spinel inclusions and slight
serpentinization. Minor glomeroporphyritic aggregates of plagioclases.
Some magnetite in groundmass very euhedral. Granular texture
between plagioclase and augite in groundmass. (Plate X.) Approx.
mode: Oliv 20%, Plag 2%, Gm 75%, Mt 3%, Ap(?) trace
- T-55 Subaerial flow 10 m. thick, Padloping Island. Subhedral to euhedral
oliv olivine phenocrysts with spinel inclusion and strong alteration to
iddingsite. Ophitic texture between plagioclase and clinopyroxene
in groundmass. Approx. mode: Oliv 25%, Plag 40%, Cpx 30%, Mt 2%,
Sp trace

B) West Greenland

- 512 Subaerial flow approx. 30 m. thick, picritic portion, east side of
oliv Suvdlua. Large fresh olivine phenocrysts (Fa_{18}) with opaque euhedral

spinel inclusion. Augite in groundmass is granular and plagioclase is partly altered to zeolite. A second zeolite fills vesicles. (Plate XIII.) Skeletal magnetite in groundmass. Approx. mode: Oliv 55%, Flag + Zeol 25%, Cpx 15%, Zeol (vesicles) 2%, Mt 1%

- 513 Segregation from 512 flow. Small subhedral to euhedral olivines with occasional spinel inclusions and partial alteration to iddingsite and chlorite. Ophitic texture between plagioclase and augite in groundmass where fresh, otherwise extensive alteration to zeolite and chlorite. Large vesicles containing at least three varieties of zeolite. (Plate XIV.) Approx. mode: Oliv 10%, Flag 35%, Cpx 35%, Zeol 10%, Mt 4%, Sp trace
- 520 Oliv +
plag +
cpx +
mt Basaltic block in breccia, head of Tasiussaq. Small euhedral phenocrysts of olivine, slightly zoned phenocrysts of augite and large phenocrysts of plagioclase showing strong oscillatory zoning and tendency towards a glomeroporphyritic texture with the augite. Fine-grained groundmass of plagioclase, augite, magnetite and chlorite. (Plate XV.) Approx. mode: Phenocrysts; Oliv 2%, Flag 14%, Cpx 4%, Mt trace. Groundmass; Flag 40%, Cpx 35%, Mt 3%, Chlor 2%
- 529 Oliv Subaerial flow 35 m. thick, west side of Suvdlua. Large subhedral and skeletal olivine phenocrysts with opaque spinel inclusions and alteration to iddingsite along cracks. Elongate skeletal olivine aligned parallel to base of lava flows. Plagioclase in part breaking down to form zeolite. Augite granular. Anhedral magnetite. Approx. mode: Oliv 50%, Flag + Zeol 30%, Cpx 15%, Mt 2%, Sp trace

- 534 Sill(?) or subaerial flow, west side of Suvdlua. Subhedral and
 oliv + skeletal phenocrysts of olivine, some with inclusions of a reddish
 plag + spinel. Also glomeroporphyritic clusters of zoned plagioclase
 mt phenocrysts. Considerable euhedral phenocrysts of magnetite, ground-
 mass variety being skeletal (ilmenite). Granular groundmass of
 plagioclase, clinopyroxene and anhedral magnetite. Minor zeolites
 in vesicles. Approx. mode: Phenocrysts; Oliv 3%, Plag 2%, Mt 3%.
 Groundmass; Plag 45%, Cpx 45%, Mt 1%, Zeol 1%, Sp trace
- 539 Dyke 2 m. wide in breccia, east side of Umiarfik. Subhedral to
 oliv euhedral fresh olivine phenocrysts with reddish spinel inclusions.
 Ophitic texture in groundmass. Approx. mode: Oliv 30%, Plag 35%,
 Cpx 30%, Mt 2%, Sp trace
- 544 Basaltic block from breccia, east side of Umiarfik. Generally euhedral
 oliv + olivine phenocrysts with inclusions of reddish spinel and minor
 plag alteration in some grains to serpentine. Skeletal phenocrysts of
 plagioclase. Groundmass consists of extremely fine-grained plagioclase
 and magnetite, microlitic clinopyroxene and glass. (Plate XVI.)
 Approx. mode: Oliv 35%, Plag (phen) 20%, Gm 45%, Sp trace
- 546 Loose block, east side of Umiarfik. Large generally subhedral olivine
 oliv phenocrysts (Fa_{18}) with reddish spinel inclusions and slight altera-
 tion along cracks and margins to iddingsite. Most of plagioclase is
 altered to zeolite and vesicles are occupied by two other types of
 zeolite. Augite fresh and poikilitic towards olivine and plagioclase.
 Approx. mode: Oliv 60%, Plag + Zeol 20%, Cpx 15%, Zeol 5%, Mt 1%,
 Sp trace

- 548 Dyke 4-5 m. wide, west side of Umiarfik. Generally euhedral
oliv + phenocrysts of olivine (Fa_{12}) with inclusions of reddish-brown
mt(?) spinel. Possible phenocrysts of magnetite. Ophitic texture in
groundmass. Approx. mode: Oliv 35%, Plag 30%, Cpx 30%, Mt 2%,
Sp trace
- 554 Dyke 1 m. wide, Nerutussoq. Partial serpentine pseudomorphs after
oliv + small olivine phenocrysts. Glomeroporphyritic clusters of oscillatory-
plag + zoned plagioclase crystals and anhedral augites. Fine-grained
cpx groundmass of plagioclase, clinopyroxene, magnetite and a yellow
alteration product. Approx. mode: Oliv 1%, Plag 15%, Cpx 5%, Gm 80%
- 578 Loose block, Skalf. Phenocrysts of completely pseudomorphed olivine,
oliv + oscillatory-zoned plagioclase (usually in glomeroporphyritic clusters),
plag + clinopyroxene and euhedral magnetite. Granular groundmass of plagio-
cpx + clase and clinopyroxene. (Plate XVII.) Approx. mode: Oliv 1%,
mt Granular groundmass. (Plate XVII.) Approx. mode: Oliv 1%,
Plag 10%, Cpx 5%, Mt 4%, Gm 80%
- 580 Thick subaerial flow, Amitsoq. Phenocrysts of completely pseudo-
oliv + morphed olivine, zoned plagioclase, zoned augite and magnetite(?).
plag + Granular groundmass. Approx. mode: Oliv trace, Plag 3%, Cpx 2%,
cpx + Gm 95%
mt(?)
- 583 Subaerial flow, Amitsoq. Almost completely pseudomorphed olivine
oliv + phenocrysts, glomeroporphyritic clusters of oscillatory-zoned plagio-
plag + clase and possible magnetite phenocrysts. Strong flowage alignment
mt(?) of groundmass plagioclase laths and granular texture with clino-
pyroxene. Alteration of a mafic mineral in the groundmass to a
mineral equivalent to that which replaces olivine. Approx. mode:
Oliv 1%, Plag 10%, Mt 8%, Gm 75%, Alteration 5%

- 586 Subaerial flow 4 m. thick, Svartenhavn. Phenocrysts of oscillatory-zoned plagioclase often in glomeroporphyritic clusters. Ophitic texture in groundmass. Interstitial material in groundmass consists of a very fine-grained brownish devitrified glass(?) and magnetite, often skeletal. Approx. mode: Plag 10%, Gm 70%, Glass(?) 10%, Mt 5%
- 589 Subaerial flow, Svartenhavn. Chlorite pseudomorphs after olivine phenocrysts, glomeroporphyritic clusters of oscillatory-zoned plagioclase and small phenocrysts of augite. Likely phenocrysts of magnetite. Groundmass of granular plagioclase, clinopyroxene and magnetite. Vesicles filled with chlorite. Approx. mode: Phenocrysts; Plag 5%, Cpx 3%, Mt 2%. Groundmass; Plag 35%, Cpx 35%, Mt 10%, Chlor 1%
- 592 Subaerial flow 15 m. thick, Tasiussap ima. Euhedral, subhedral and skeletal phenocrysts of olivine with abundant opaque spinel inclusions. Also phenocrysts of magnetite in the groundmass as well as elongated groundmass varieties (ilmenite?). Granular texture in groundmass between plagioclase and cpx. Vesicles filled by two types of zeolite. Approx. mode: Oliv 30%, Mt 3%, Gm 65%, Sp trace
- 593 Subaerial flow 3 m. thick, Tasiussap ima. Large subhedral olivine phenocrysts (Fa_8) with inclusions of a large opaque spinel as well as a minute reddish spinel and showing minor alterations along margins and cracks to serpentine. Also phenocrysts of magnetite. Granular texture in groundmass between plagioclase and augite. Partial breakdown of plagioclase to zeolite which is also present in vesicles. Approx. mode: Oliv 50%, Plag 15%, Cpx 25%, Zeol 10%, Sp 1%

- 594 Subaerial flow, Tasiussap ima. Possible pseudomorphs after olivine
 oliv(?) phenocrysts (and in groundmass?). Large glomeroporphyritic clusters
 + plag of oscillatory-zoned plagioclases. Occasional phenocrysts of augite
 + cpx usually associated with plagioclase clusters. Likely phenocrysts
 + mt of magnetite. Granular texture in olivine(?) - plagioclase - augite -
 magnetite groundmass. Approx. mode: Phenocrysts; Oliv 1%, Plag 5%,
 Cpx trace. Groundmass; Plag 35%, Cpx 35%, Mt 10%, Alteration 10%
- 598 Subaerial flow, 3 m. thick, Tasiussap ima. Partly serpentinized pheno-
 oliv + crysts of olivine with inclusions of opaque and reddish spinel.
 plag + Glomeroporphyritic clusters of clinopyroxene. Magnetite phenocrysts(?).
 cpx + Groundmass texture is essentially granular. Groundmass clinopyroxene
 mt(?) is zoned outwards to a brown rim (titanaugite?). Partial breakdown
 of plagioclase to zeolite. Approx. mode: Oliv 5%, Plag trace, Cpx
 2%, Mt 2%, Gm 35%, Zeol 5% Sp trace
- 599 Subaerial flow 4 m. thick, Ege Bay, Tasiussap ima. Generally sub-
 oliv + hedral and skeletal phenocrysts of olivine with minor opaque spinel
 plag + only and partial alteration to serpentine(?) along cracks. Strongly
 cpx + zoned phenocrysts of plagioclase often in glomeroporphyritic clusters
 mt and generally subhedral phenocrysts of augite also occasionally in
 glomeroporphyritic aggregates. Two varieties of magnetite are sub-
 hedral (phenocrysts?) and skeletal (groundmass?). Granular texture
 in groundmass. At least two varieties of zeolite occur as vesicle
 fillings. Approx. mode: Oliv 15%, Plag 25%, Cpx 10%, Mt 2%, Gm 45%,
 Zeol 2%, Sp trace
- 600 Subaerial flow, Ege Bay. Large, generally subhedral (zoned?) pheno-
 oliv + crysts of olivine without spinel inclusions and with partial altera-

- plag +
cpx +
mt(?) tion to iddingsite. Also phenocrysts of plagioclase showing oscillatory zoning and a few apparently unzoned phenocrysts of augite. Phenocrysts of magnetite possible. Granular texture in groundmass between plagioclase and clinopyroxene. Magnetite interstitial. Approx. mode: Oliv 5%, Plag 2%, Cpx 1%, Gm 80%, Mt 10%
- 625 Subaerial very vesicular flow, Arfertuarssuk. Large, partly corroded phenocrysts of alkali feldspar (anorthoclase?). Ferromagnesian minerals, possibly hornblende, completely pseudomorphed. Groundmass extremely fine-grained with trachytic texture. (Plate XIX.) Approx. mode: Anortho 20%, Ferromag 5%, Gm 80%
- 629 Centre of dyke 4 m. wide, Arfertuarssuk. Somewhat corroded and altered phenocrysts of olivine, phenocrysts of zoned (often oscillatory) plagioclase frequently in glomeroporphyritic aggregates and large phenocrysts of augite showing zoning on the rims to titanaugite. Magnetite possible phenocrysts. All three silicate phenocryst phases plus magnetite present in groundmass in a granular to partly ophitic texture. Needles of apatite present. (Plate XVIII.) Approx. mode: Oliv 7%, Plag 45%, Cpx 80%, Mt 8%, Gm 10%
- 630 Intrusion(?) at least 30 m. thick, Arfertuarssuk. Large euhedral phenocrysts of anorthoclase and a second alkali feldspar(?) apparently undergoing resorption. (Plate XX.) Also phenocrysts of aegirine augite. Approx. mode: Anortho 15%, Cpx 5%, Gm 80%
- 635 Subaerial flow, 5 m. thick, Arfertuarssuk. Phenocrysts of olivine completely altered to iddingsite, plus serpentine(?). Individual and glomeroporphyritic zoned phenocrysts of plagioclase, the latter often

associated with clusters of augite phenocrysts. Also euhedral magnetite phenocrysts. Groundmass very fine-grained plagioclase + clinopyroxene + magnetite. Approx. mode: Oliv 2%, Plag 20%, Cpx 2%, Mt 10%, Gm 65%

- 636 Subaerial flow, 7 m. thick, Arfertuarssuk. Completely pseudomorphed phenocrysts of olivine (replaced by chlorite and carbonate?), strongly zoned phenocrysts of plagioclase, fresh, slightly zoned phenocrysts of augite often in glomeroporphyritic aggregates with plagioclase, and phenocrysts of magnetite(?). Granular groundmass. Approx. mode: Oliv 2%, Plag 20%, Cpx 2%, Mt 6%, Gm 70%
- 638 Boulder, east side of Arfertuarssuk. Phenocrysts of olivine completely altered to carbonate and an unknown mineral. Large phenocrysts of plagioclase showing very strong, mostly normal zoning and a few small augite phenocrysts. Granular groundmass. (Plate XXI.) Approx. mode: Pseudo Oliv 10%, Plag 20%, Cpx 5%, Gm 60%, Mt 5%
- 640 Loose block, South Coast. Large subhedral olivine phenocrysts with mainly opaque spinel inclusions. Groundmass consists of plagioclase laths incorporated in large poikilitic grains of augite, also development of skeletal magnetite and vesicle fillings of zeolite and chlorite. (Plate XXII.) Approx. mode: Oliv 55%, Plag 25%, Cpx 15%, Mt 1%, Zeol + Chl 5%, Sp trace
- 641 Loose block, South Coast. Generally subhedral olivine phenocrysts with only minor inclusions of a nearly opaque spinel. Alteration of olivine along cracks to serpentine and magnetite. Phenocrysts of magnetite likely. Granular to ophitic relationship between plagio-

clase and clinopyroxene in groundmass. Magnetite skeletal. Approx.
mode: Oliv 35%, Plag 30%, Cpx 30%, Mt 2%, Sp trace

642 Subaerial flow 2 m. thick, South Coast. Large, mainly skeletal
oliv + phenocrysts of olivine with inclusions of both opaque and reddish
mt spinel. Possible phenocrysts of magnetite approaching euhedral
shapes whereas groundmass opaques are skeletal. Flow alignment of
plagioclase in groundmass and granular relationship with clinopyroxene. Zeolites in vesicles. Approx. mode: Oliv 35%, Mt 1%,
Zeol 2%, Gm 60%, Sp trace

643 Loose block, South Coast. Generally subhedral olivine phenocrysts
oliv of widely variable size (some groundmass?) with inclusions of mainly
the opaque spinel. Slight alteration of olivine to iddingsite.
Granular texture in groundmass. Zeolitic patches with inclusions of
rutile(?) or spinel(?). Approx. mode: Oliv 40%, Plag 25%, Cpx 25%,
Zeol 15%, Mt 1%

648 Basaltic block from breccia, Umivik Bay. Generally euhedral or
oliv + skeletal phenocrysts of olivine with abundant reddish spinel inclu-
plag sions. Also phenocrysts of plagioclase some of which look feathery.
Reddish spinels in glass. Glassy groundmass. (Plate XXIII.) Approx.
mode: Oliv 30%, Plag 5%, Gm 65%, Sp trace

649 Loose block, Umivik Bay. Euhedral to subhedral olivine phenocrysts
oliv + (Fa₁₅) with abundant spinel inclusions, all of the opaque variety.
mt Also magnetite phenocrysts. Alteration of plagioclase to zeolite in
the groundmass and augite occurs as fairly large grains which have
well-developed faces if grown into a cavity now occupied by further

zeolitic material. More rutile(?) associated with zeolitic cavities.
 Approx. mode: Oliv 45%, Plag + Zeol 25%, Cpx 20%, Zeol (vesicles)
 8%, Mt 2%, Sp trace

- 651 Oliv + plag Basaltic block from breccia, Umivik Bay. Olivine phenocrysts, mainly euhedral and skeletal, with abundant inclusions of isotropic reddish spinels which are also found in the glassy groundmass. Also a few phenocrysts of skeletal plagioclase. Approx. mode: Oliv 35%, Plag 1%, Glass and Gm 65%, Sp trace
- 655 Oliv + mt Subaerial flow 2 m. thick, Umivik Bay. Subhedral phenocrysts of olivine (Fa_{11}) with inclusions of both reddish and opaque spinel. Magnetite probable phenocrysts. Ophitic texture in groundmass. Minor patches of chlorite in groundmass. Approx. mode: Oliv 30%, Plag 35%, Cpx 30%, Mt 2%, Chlor 2%, Sp trace
- 658 Oliv + plag Glassy breccia, Kanguissap ima. Isotropic blocks of sideromelane with a darkened rim of palagonite separated from one another by fibropalagonite. Phenocrysts of olivine, mainly skeletal, with reddish spinel inclusions and also phenocrysts of plagioclase in the glass. Occasional patches of chlorite. (Plate XXIV.) Approx. mode: Oliv 25%, Plag trace, Siderom 40%, Palag 5%, Fbpalag 25%, Chlor 5%, Sp trace
- 661 Oliv Subaerial flow, 3 m. thick, South Coast. Olivine phenocrysts completely pseudomorphed by an unidentifiable brown mineral which also occupies all the interstitial areas in the groundmass. Rock is aphyric apart from the 1% of pseudomorphed olivines. Granular texture in groundmass. Approx. mode: Brown Min 15%, Plag 45%, Cpx 40%, Mt 2%

- 662 Marginal chill of a dyke, 8 m. wide, South Coast. Phenocrysts of oliv + olivine partly serpentinized and bearing only minor opaque spinel plag + inclusions. Zoned phenocrysts of plagioclase and augite often in cpx + glomeroporphyritic aggregates. Possible magnetite phenocrysts. mt(?) Granular texture in groundmass. Approx. mode: Oliv 2%, Flag 5%, Cpx 10%, Mt 3%, Gm 80%
- 664 Subaerial flow, 2 m. thick, South Coast. Iddingsite and serpentine oliv pseudomorphs after olivine phenocrysts. Well-developed ophitic texture in groundmass although a lot of the plagioclase has now broken down to zeolite. Two other varieties of zeolite occupy small vesicles. Approx. mode: Pseudo Oliv 5%, Flag + Zeol 45%, Cpx 45%, Zeol (vesicles) 2%, Mt 3%
- 669 Subaerial flow, 7 m. thick, South Coast. Subhedral phenocrysts of oliv + olivine with spinel inclusions predominantly of the opaque variety mt and alteration of margins to iddingsite. Also phenocrysts of magnetite. Groundmass very fine-grained and granular. Small vesicles with infillings of zeolite. Approx. mode: Oliv 30%, Mt 2%, Zeol 3%, Gm 65%
- 670 Thick sill, Qordlortup. Coarse-grained dolerite with olivines both corroded and partially altered to iddingsite. Olivines tend to be enclosed in augite rather than plagioclase and are more corroded in contact with augite than with plagioclase. Doleritic texture between augite and plagioclase, both of which are zoned. No orthopyroxene. Interstitial material consists of magnetite, a green fibrous mineral (chlorite?) and small apatite needles. (Plate XXV.) Approx. mode: Oliv 10%, Plag 40%, Cpx 40%, Mt 5%, Chlor 5%

671 Sill(?), Firefjeld. Subhedral olivine phenocrysts with few spinel
oliv + inclusions and partial alteration to serpentine. Magnetite a pos-
mt(?) sible phenocryst phase. Fine-grained granular groundmass. Approx.
mode: Oliv 15%, Mt 3%, Plag 40%, Cpx 40%, Sp trace

Plate I. Unconsolidated white sands with interbedded coal and black shale,
north coast of Padloping Island.

Plate II. Stack at Cape Searle showing giant cross-bedding in volcanic breccia
unit followed by a section of approximately 300 m. of picritic
flows generally thinning upwards.

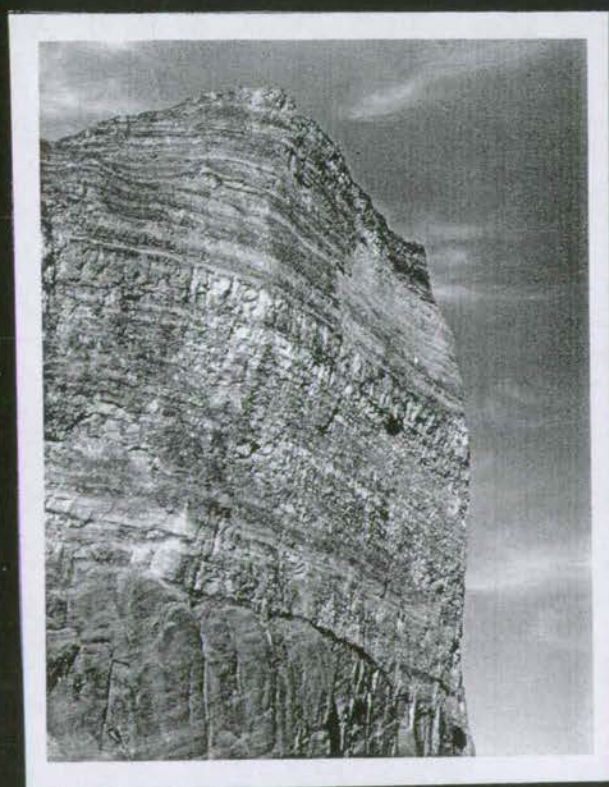


Plate III. Macro-texture of orange volcanic breccia with talus slope in foreground, Cape Searle.

Plate IV. Lowermost black breccia grading up into a subaerial sequence of flows upon which the upper orange breccias, with conspicuous cross-bedding, have been deposited.



Plate V. AA-19 (x7). Intra-flow differentiate, from same flow as AA-30 (Plate VI), showing large twinned augite, zoned plagioclase and a small interstitial patch with skeletal magnetite and myrmekite(?) on the left edge of the photomicrograph.

Plate VI. AA-30 (x7). Olivine-rich base of thick flow showing cumulus olivine, often euhedral towards intercumulus plagioclase but anhedral when enclosed by augite.

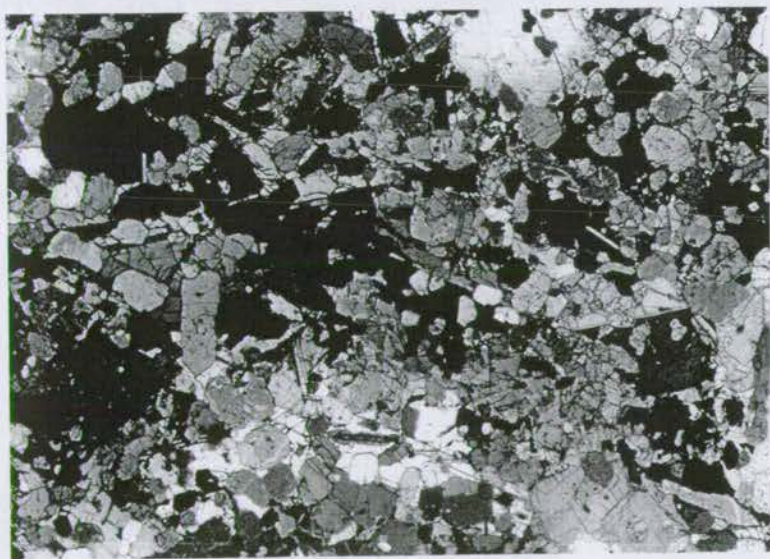
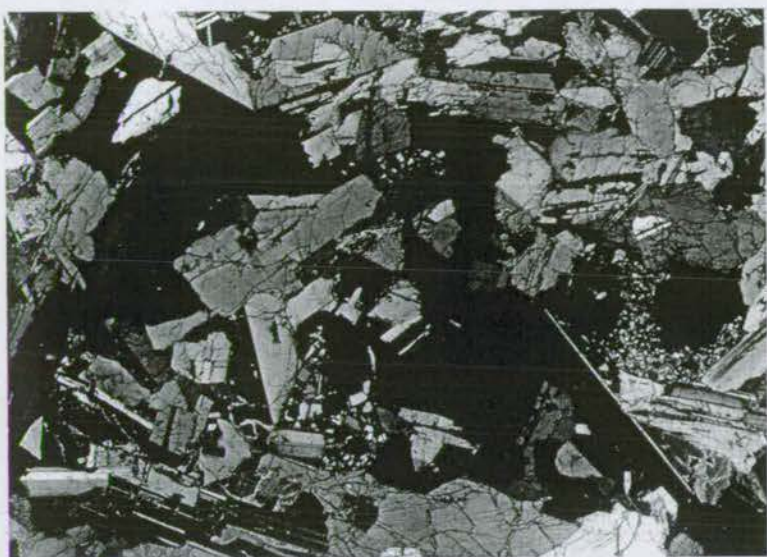


Plate VII. C-4a (x30). Some of the radially arranged plagioclase laths amongst olivines in a spherule from a variolitic flow.

Plate VIII. E-2 (x30). Hyaloclastite from black breccia, showing skeletal phenocrysts of olivine with inclusion of opaque spinel and glass in sideromelane darkened at the margins to palagonite. Vesicles contain zeolites.

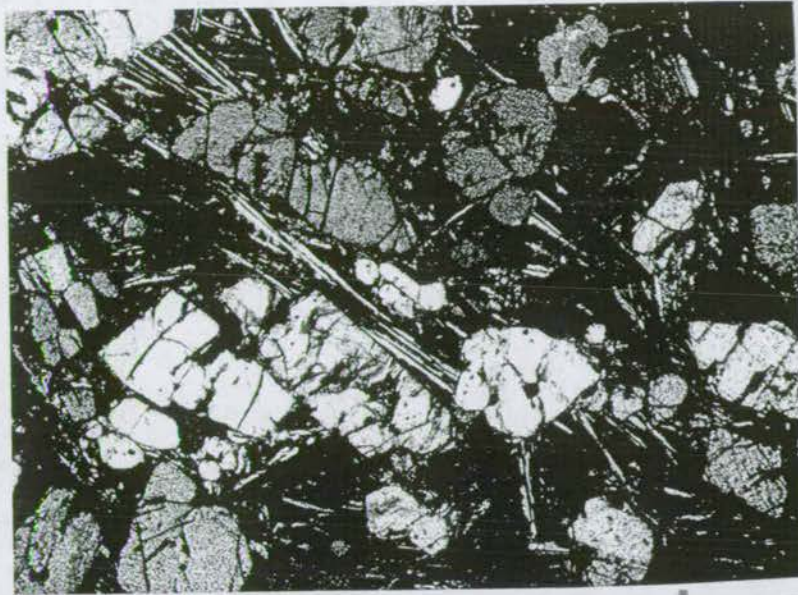


Plate IX. I-64 (x7). Typical Group II composition showing a profusion of olivine microphenocrysts (enclosing euhedral spinels) in a fine-grained groundmass.

Plate X. T-47 (x30). Dyke rock showing both skeletal olivine and some which have undergone partial serpentinization.

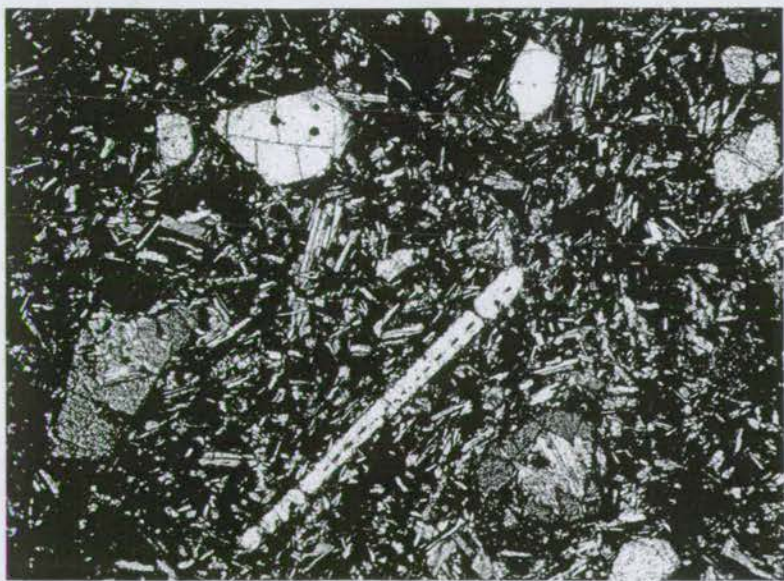
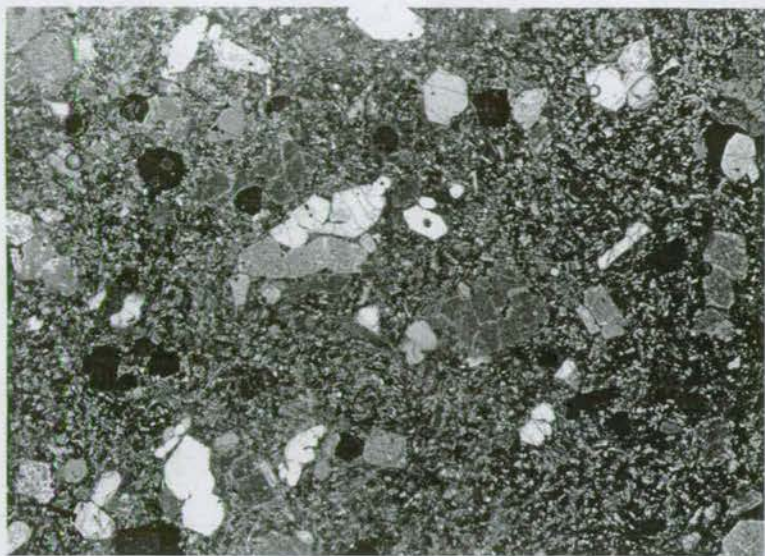


Plate XI. ROB (x7). Orange breccia (plane polarized light) showing skeletal olivines enclosed in sideromelane with darkened margins of palagonite. Amorphous accumulations of opaque ferromanganiferous(?) oxides in the finely comminuted material between larger pieces of sideromelane.

Plate XII. ROB (x7). Same area as in Plate XI but with crossed polars to show isotropy of sideromelane and palagonite but birefringence of fibropalagonite.

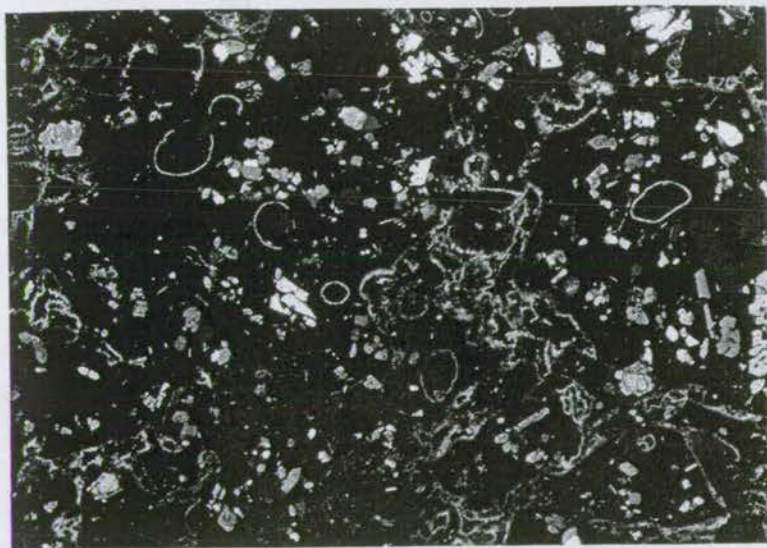


Plate XIII. 512 (x7). Typical Group I composition with large phenocrysts of olivine. Groundmass plagioclase in this specimen is breaking down to zeolite.

Plate XIV. 513 (x7). Olivine-poor intra-flow differentiate from same flow as 512.

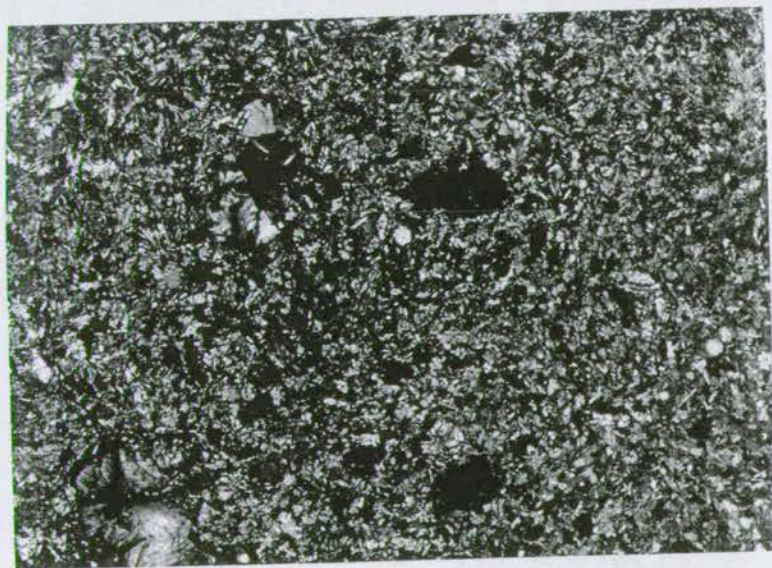
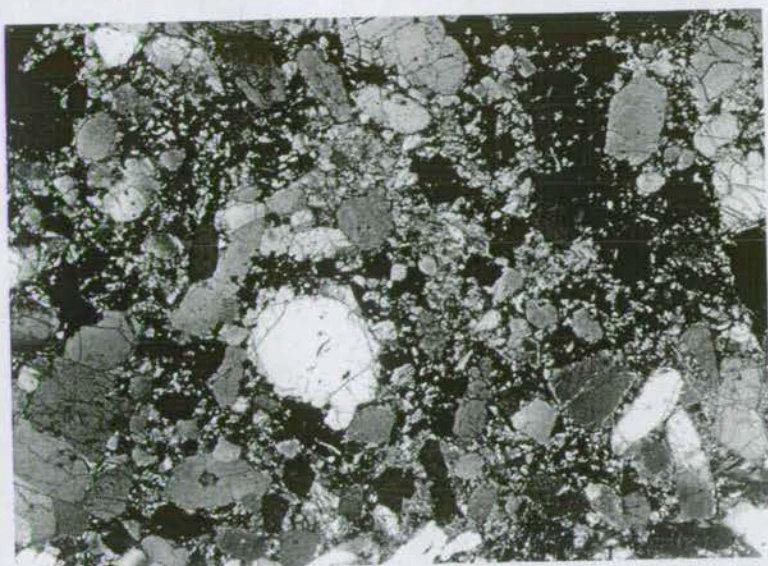


Plate XV. 521 (x7). Glassy portion of same flow from which sample 520 was taken showing phenocrysts of olivine and augite but predominantly plagioclase (one of which shows oscillatory zoning), in a ground-mass of sideromelane and fibropalagonite.

Plate XVI. 544 (x30). Typical Group II composition (see Plate IX).



Plate XVII. 578 (x7). Feldspar-phyric basalt (plane polarized light) showing phenocrysts of plagioclase, augite, magnetite and possible pseudomorphs after olivine (large opaque areas).

Plate XVIII. 629. One of the most evolved basalts collected on Svartenhuk showing a predominance of plagioclase and augite phenocrysts.

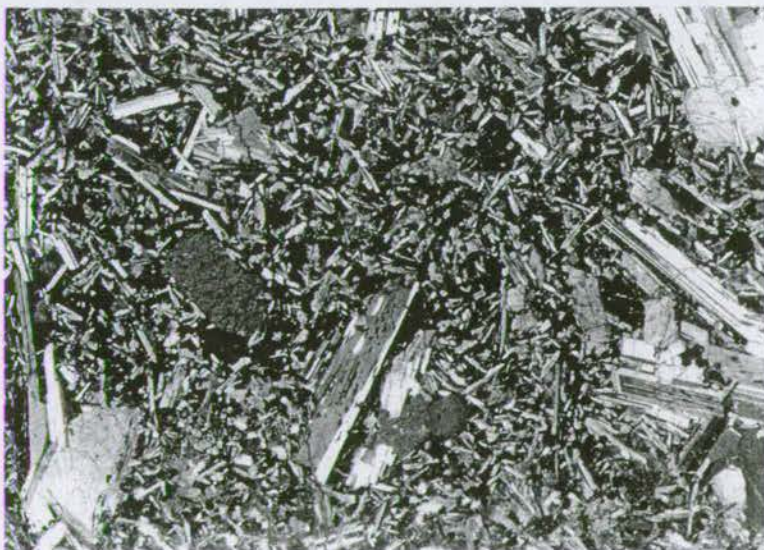
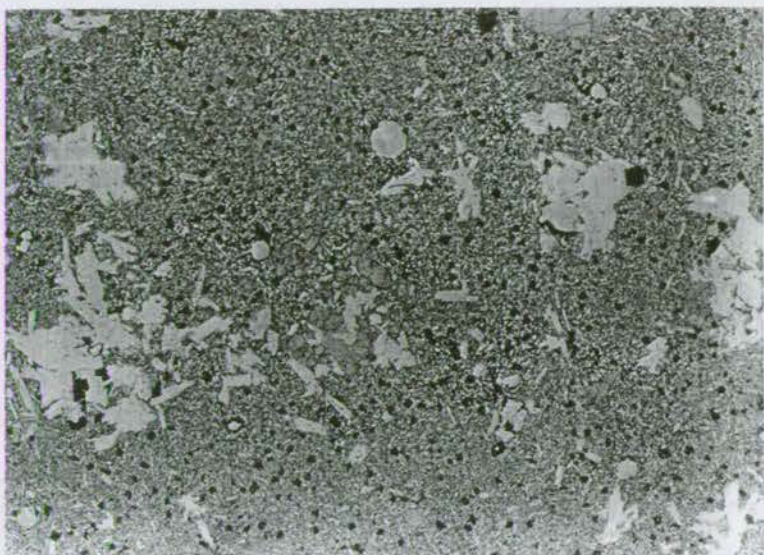


Plate XIX. 625. Vesicular subaerial trachyte from Arfertuarssuk.

Plate XX. 630. Trachyte intrusion(?) from Arfertuarssuk showing large phenocrysts of alkali feldspar.

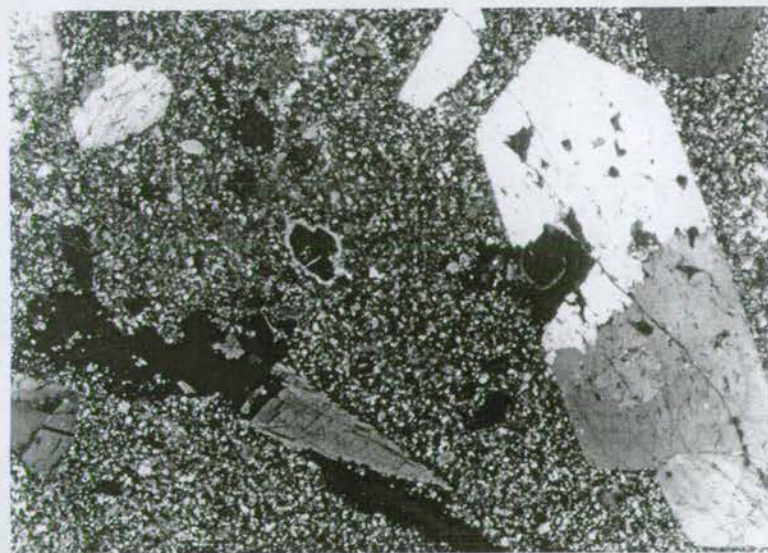


Plate XXI. 638 (x30). Feldspar-phyric basalt.

Plate XXII. 640 (x7). Large phenocrysts of olivine in a typical Group I composition.

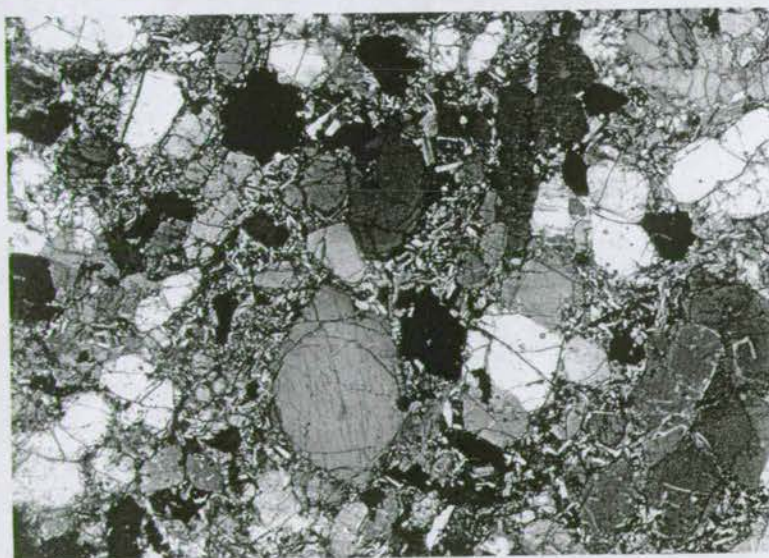


Plate XXIII. 648 (x7). Rapidly cooled block from breccia showing micro-phenocrysts of olivine and plagioclase.

Plate XXIV. 658 (x7). Glassy picritic breccia showing skeletal olivines.

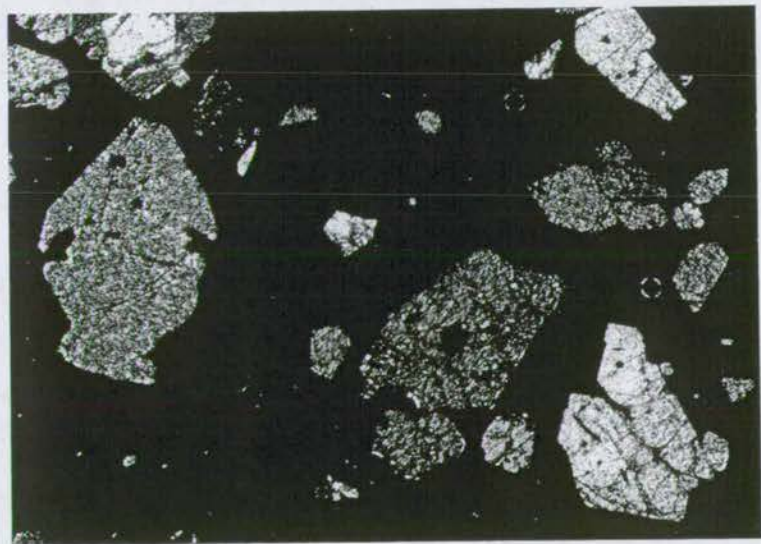
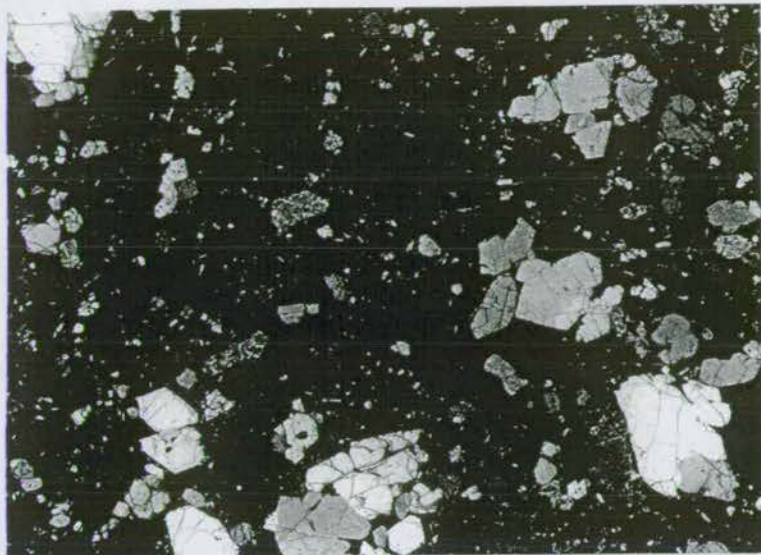


Plate XXV. 670 (x7). Olivine dolerite sill (plane polarized light) showing anhedral, corroded olivines with iddingsite in cracks and with doleritic texture between plagioclase and augite.



APPENDIX BANALYTICAL METHODSI. Sample Preparation

Altogether 81 hand specimens were reduced to rock powder and most were analyzed for 23 components. First the process of analysis is logically traced.

Field specimens were first scrubbed under hot, running water and then rinsed with distilled water in order to remove adhering soil particles and other foreign matter. Up to 700 grams of the specimen were then reduced on a "Cutrock" hydraulic splitter to chips with a maximum dimension of about 4 cm., and in the process any weathered surfaces were discarded. The fresh chips were then crushed to -24 mesh on a tungsten carbide plate using a WC pestle. This coarse powder was then coned and quartered until a sample of 75-150 grams was obtained which was finally ground to -97 mesh in an agate ball mill. The ground material was stored in capped glass bottles and was dried overnight at 110°C. before analysis of any element or preparation of fusion discs for the X-ray analysis took place.

Possible sources of contamination include Fe and Mn from the jaws of the "Cutrock", cobalt and tungsten from the WC plate and pestle, which have a binder consisting of 10% Co, and silica from the agate ball mill. Only the cobalt contamination was quantitatively investigated and was found to be unacceptably high; therefore, Co was not analyzed in these rocks. Otherwise, the extreme care taken during sample preparation is believed to have kept contamination from the other sources mentioned above to below detectable limits.

II. Analytical Procedure

Roughly speaking, the 81 analyses may be broken into two groups of 11

and 70 specimens. The first batch, consisting of samples A-5, 6; C-56; DX-9, 18, 24, 48, 52; E-2; P-5 and T-55, was analyzed completely in the wet lab with DX-24 and 48 being done entirely in duplicate. Sample E-2 was analyzed once by Dr. E.L.P. Mercy and in duplicate by the author. In fact, the SiO_2 , MgO and CaO in the remaining 8 samples of the first batch were the only major oxides in the two batches analyzed on the basis of a single determination. In both batches all minor elements determined in the wet lab were analyzed at least in duplicate. Of the trace elements, Ba, Sr and Ni were duplicated after an interval of several months.

The second batch was analyzed for major elements by X-ray fluorescence (XRF) never relying on less than two determinations from a single disc, often duplicating discs, and duplicating 12 of the 70 fusions. Of the minor elements done in the wet lab in the first batch, Ti and Mn were transferred to XRF in the second batch.

Six specimens (A-5, 6; DX-47; FD-11; I-102; and P-5) were run for some trace elements on a Hilger and Watts EL78 Littrow Optical Spectrograph, and the following averages were obtained: Li 10 ppm., V 200 ppm., Cr 1500 ppm., Ni 450 ppm., Cu 100 ppm., Sr < 200 ppm. and Ba < 100 ppm. Later work with the X-ray Spectrograph confirmed the general levels of all but the first two, neither of which lends itself to easy determination by the XRF technique.

In the wet lab a Unicam SP500 Spectrophotometer was used for determination of TiO_2 , MnO and P_2O_5 , and an EEL Model A Flame Photometer for Na_2O and K_2O . A modified Philips FW 1540 X-Ray Spectrograph was used for elements determined by XRF. Below is a brief description of the methods used; details are given only when a suitable reference could not be cited.

A) First Batch: Major Elements

Silica, Calcium and Magnesium - classical gravimetric technique, see Peck (1964).

Alumina - DCTA method, see Mercy and Saunders (1966).

Total Iron as Fe_2O_3 - silver reductor method, see Mercy and Saunders (1966).

Ferrous Iron - Method: To 0.5 gm. of rock powder in a Pt crucible add 5 ml. of 50% freshly boiled H_2SO_4 and 10 ml. of HF. Cover with lid and place on hotplate to boil within 3 minutes. Boil for 5 minutes. Immerse quickly in boric acid solution (10 gm. H_3BO_3 + 400 ml. distilled water). Add 10 ml. of indicator (100 ml. H_2O + 100 ml. H_3PO_4 + 0.02 gm. sodium diphenylamine sulphonate). Titrate with standard potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) solution.

B) First Batch: Minor Elements

Titanium - tiron method, see Yoe and Armstrong (1947).

Manganese - see Richards (1930).

Phosphorus - see Baadsgaard and Sandell (1954).

Alkalies - Method: To 0.1 gm. of sample in Pt crucible add 4 ml. HNO_3 and 5 ml. HF and dry on sand bath over several hours. Add 4 ml. HNO_3 and 2 ml. HF and dry as before. Add 2 ml. 1:1 H_2SO_4 and place on medium hotplate and allow to fume dry. Hold crucible over low flame to dull red heat to remove last traces of fumes. Cool, add distilled water and bring to incipient boiling. Filter into beakers, washing filter paper six times with very hot distilled water. Add 0.5 ml. of 10% H_2SO_4 and make up to mark in 100 ml. flask. Run against identically acidified standards in flame photometer.

Water - Lead oxide-lead chromate fusion, see Shapiro and Brammoch (1956), except fusion mixture as per Peck (1964).

C) Second Batch: Major Elements

Silica, Alumina, Total Iron, Magnesium, Calcium - XRF, see Table B-1.

Ferrous Iron - as First Batch.

D) Second Batch: Minor Elements

Titanium, Manganese - XRF, see Table B-1.

Phosphorus, Alkalies, Water - as First Batch.

Carbon Dioxide - see Welcher (1963).

III. X-Ray Fluorescence Technique

The theory and application of XRF spectroscopy is well described by Jenkins and De Vries (1967). In short, it is a comparative method which measures the intensity of characteristic secondary X-rays emitted by the sample relative to known standard materials run at the same time. The sample preparation technique described below enables the analyst to construct linear calibration curves, from which is read directly the concentration of any particular element, given its count rate or peak to background ratio.

The fusion technique of sample preparation is long and arduous, but necessary in order to homogenize the sample, eliminate mineral and grain size effects, and standardize the mass absorptions of the rocks, so that peridotites and granites can be read off the same calibration curve. Powdered rock sample, lanthanum oxide (heavy element absorber) and lithium tetraborate (diluent and flux) are weighed out in the proportions 1:1:8, with 0.7500 grams being a convenient sample weight. These three constituents are mixed and transferred to a carbon crucible, which is then placed in a muffle furnace at 700°C. The temperature is then raised to 1050°C., at which the sample is kept for a period of 20 minutes before being removed to cool in air until cool enough to

touch. The fused glass bead is removed from the crucible, and to it is added sufficient lithium tetraborate to restore the original, intended 9:1 dilution of the sample; (loss of volatiles on fusion effectively increases the weight fraction of the sample, and this effect must be counterbalanced by the addition of further diluent).

The bead and added lithium tetraborate are then ground to -200 mesh in a tungsten carbide ball mill. The fine powder is dried at 110°C. and stored in an airtight bottle until pressed discs are required for the XRF spectrograph. Each disc is made in a 15-ton ram from the bead powder with a backing of boric acid 0.5-1.0 cm. thick. Since the working surface of the disc is susceptible to deterioration with time, it was found that the life of the disc could be prolonged by storing it in a warming oven. A lowering of the count rate is the first indication of this decay and is usually noticeable on the Mg peak about a month after pressing the disc. Given these conditions, each disc was analyzed for all elements within ten days of pressing, beginning with the lower atomic numbers and working up.

Standards for making the calibration curves were prepared in exactly the same manner. The most useful of these for basalt analysis included the U. S. National Bureau of Standards numbers NBS 1a, 76, 77, 91 and 102; the U.S.G.S. numbers AGV-1, BCR-1, DTS-1, G-2, GSP-1 and PCC-1 (Flanagan, 1967; Carmichael et al., 1968); also a peridotite (353) analyzed by Dr. E.L.P. Mercy, the Milford Granite and the 11 samples analyzed in the first batch of analyses. Synthetic standards prepared by Mr. G. R. Angell were especially useful for trace element determinations, as many of the above standards have not yet been assigned official values for many of the rarer trace elements.

Table B1 Operating Conditions for X-Ray Spectrograph

Element	¹² Mg	¹³ Al	¹⁴ Si	²⁰ Ca	²² Ti	²⁴ Cr	²⁵ Mn	²⁶ Fe	²⁸ Ni	²⁹ Cu	³⁰ Zn	³¹ Ga	³⁷ Rb	³⁸ Sr	³⁹ Y	⁴⁰ Zr	⁵⁶ Ba	⁸² Pb
Generator (KV/ma)	50/28	60/20	60/20	40/20	40/20	50/20	50/24	40/20	40/20	50/20	50/20	80/24	50/24	50/24	50/20	50/20	60/20	80/24
Analyzing Crystal	ADP	PE	PE	LiF	LiF	PE	LiF	LiF	LiF	LiF(110)	LiF	LiF	LiF	LiF	LiF(110)	LiF	Topaz	LiF
Count Rate (cps/%)	6	43	440	2300	1400	-	1425	1120	-	-	-	-	-	-	-	-	-	-
(P/B/ppm)	-	-	-	-	-	0.007	-	-	0.011	0.011	0.008	0.025	0.004	0.005	0.004	0.004	0.008	0.005
Theoretical LLD (ppm)	-	-	-	-	-	6	-	-	3	6	2	4	1	3	5	2	12	6

- Additional Notes:
1. Cr Tube for Z = 12-22; otherwise W tube except Z = 31 where Mo was used.
 2. K line measured in every case.
 3. Coarse collimator Z = 12-20 and Z = 31; otherwise fine collimator.
 4. Vacuum and gas flow proportional counter used for Z = 12-26; otherwise non-vacuum and scintillation counter used.
 5. Peak counts only measured in Z = 12-22, 25 and 26 on fusion discs; otherwise Peak/Background ratio measured on -97 mesh rock powder.
 6. Formula for lower limit of detection (LLD) = $3/m \sqrt{R_b/T_b}$ where m = net cps/ppm, R_b is the count rate on the background in cps and T_b is total counting time on the background in seconds.
 7. V_{Kβ} interference ignored; therefore Cr values quoted are slightly high.
 8. Rb_{Kβ} interference on Y peak; therefore subtracted 1/5 Rb_{Kα} from Y_{Kα} before ratioing.
 9. Sr_{Kβ} interference on Zr peak; therefore subtracted 1/12 Sr_{Kα} from Zr_{Kα} before ratioing.

TABLE B2

Precision of Gravimetric Analyses

	<u>E-2₁ (ELPM)*</u>	<u>E-2₂</u>	<u>E-2₃</u>	<u>Dx-24₁</u>	<u>Dx-24₂</u>	<u>Dx-48₁</u>	<u>Dx-48₂</u>
SiO ₂	45.14	45.15	45.15	45.95	46.01	47.32	47.35
R ₂ O ₃	24.70	24.72	24.71	24.78	24.73	27.35	27.45
CaO	9.03	9.05	9.01	10.29	10.12	11.69	11.68
MgO	13.09	13.19	13.07	16.71	16.92	10.78	10.76

* Analyzed by Dr. E.L.P. Mercey

TABLE B3
Precision of X-ray Fluorescent Analysis

	Range (Wt%)		Mean (Wt%)	Tolerance Limits* (Wt%)	Avg. Difference between 2 Accepted Values (Wt%)	Avg. Difference as % of Means
	Low	High				
SiO ₂	41.9	51.5	46.1	0.40	0.15	0.32%
TiO ₂	0.38	3.12	1.24	0.02	0.01	0.08%
Al ₂ O ₃	5.7	16.7	11.7	0.10	0.05	0.42%
Total Fe as Fe ₂ O ₃	8.8	15.4	12.8	0.15	0.06	0.47%
MgO	4.7	30.6	15.2	0.25	0.11	0.72%
CaO	5.1	14.7	10.2	0.08	0.03	0.29%
				<hr/>	<hr/>	
TOTALS				1.00	0.41	

* The tolerance limit is defined as the maximum allowable difference between two determinations before an average was taken

IV. Precision and Accuracy of Gravimetric Analyses

The question of precision in classical gravimetric analysis has been extensively studied by Fairbairn et al. (1951) and Stevens et al. (1960) in large co-operative efforts on the standard materials G-1 and W-1. A study of accuracy was undertaken by Fairbairn and Schairer (1952) and Fairbairn (1953) on a synthetically produced glass of a granitic composition close to G-1. Only by knowing the true composition in advance is it possible to make an evaluation of accuracy. None of the above studies offers a solution to the investigation of accuracy in a single analysis, nor has any solution been advanced since. However, an idea of the precision of the gravimetric determinations performed on samples E-2, DX-24 and 48 is suggested in Table B-2, although insufficient data are available here for proper statistical treatment.

V. Precision and Accuracy of X-Ray Analyses

The contents of Table B-3 give an idea of the degree of precision obtainable in the analysis of the major elements. It may be seen from the last column that the error introduced by counting effects would only rarely rise above 1% of the amount present. Added to this error must also be the incalculable errors which can creep into the lengthy sample preparation technique. These include the difficulty of weighing dried sample in a humid atmosphere and the possible loss of material in several stages of handling.

Because it is a comparative method, the accuracy of XRF analysis is limited by the quality of the analyzed material which is used as standards. The total of all oxides is a poor criterion for accuracy, as it can mask large errors, but in any other way accuracy is difficult to measure. In the end, analyses with totals of $100.0 \pm 0.8\%$ were considered acceptable; the mean total and standard deviation were $99.83 \pm 0.13\%$.

Calibration curves for trace elements were based on a wide variety of standard materials, including natural rocks, NBS synthetics and various departmental synthetics. Samples and standards were irradiated as -97 mesh powder supported in the sample holders by mylar. The computation of a peak/background ratio is a crude means of eliminating differential mass absorption effects, but in the case of each element a good line was readily fitted to the half dozen or more standards used.

The most difficult of all the elements to analyze was barium, principally because of the sharp rise in background counts, with consequent low peak/background ratios. Even so, the result of 45 consecutive runs on W-1 uncorrected for drift gave a standard deviation of only 6.5 ppm. at the 160 ppm. level. All other elements had substantially lower atomic numbers and also had drift corrections applied; therefore, it may be concluded that precision was considerably better than that obtained for barium, although actual figures cannot be quoted.

In the determination of Ga, Rb, Y and Pb it was important to choose the duration and number of counting intervals which would render the theoretical lower limit of detection (LLD) as small as reasonable time permitted. The calculation of the LLD is such that a peak is not assumed to exist unless the counts at the peak position are three times greater than the standard deviation of the background counts, i.e. 99% confidence that the peak is real. Only for Pb was the LLD so high that not a single sample exceeded its value; peak background ratios indicated that Pb was less than 2 ppm. in all specimens, but this can be stated with only 33% confidence.

BIBLIOGRAPHY

- BAADSGAARD, H. and SANDELL, E.B., 1954. Photometric Determination of Phosphorus in Silicate Rocks. *Anal. Chim. Acta* 11, 183-187.
- BARRETT, D.L., 1966. Lancaster Sound Shipborne Magnetometer Survey. *Cdn. J. Earth Sci.* 3, 223-235.
- BERNIER, J.E., 1910. Report on the Dominion of Canada Government Expedition to the Arctic Islands and Hudson Strait on Board the D.G.S. "Arctic". Govt. Printing Bureau, Ottawa.
- BIDGOOD, D.E.T. and HARLAND, W.B., 1961. Palaeomagnetic Studies of Some Greenland Rocks. *Geology of the Arctic*, Vol. 1, 285-292, Editor G.O. Raasch, Univ. of Toronto Press.
- BIRCH, F., 1952. Elasticity and Constitution of the Earth's Interior. *J. Geophys. Res.* 57, 227-286.
- _____, 1961. The Composition of the Earth's Mantle, *Geophys. J. Roy. Astron. Soc.* 4, 285-311.
- BIRKELUND, T., 1965. Ammonites from the Upper Cretaceous of West Greenland. *Medd. om Grøn.* 179, Nr. 7.
- BLACKADAR, R.G., 1964. Basic Intrusions of the Queen Elizabeth Islands, District of Franklin. *Geol. Surv. Canada Bull.* 97.
- BONATTI, E., 1967. Mechanisms of Deep-Sea Volcanism in the South Pacific. *Res. Geochem.*, Vol. 2, 453-491, Editor P.H. Abelson, Wiley, New York.
- _____, and NAYUDU, Y.R., 1965. The Origin of Manganese Nodules on the Ocean Floor. *Am. J. Sci.* 263, 17-39.
- BOWEN, N.L., 1915. The Crystallization of Haplobasaltic, Haplodioritic and Related Magmas. *Am. J. Sci.* 40, 161-185.
- _____, 1928. The Evolution of the Igneous Rocks. Princeton University Press.

- BRIDGWATER, D., 1967. Feldspathic Inclusions in the Gardar Igneous Rocks of South Greenland and their Relevance to the Formation of Major Anorthosites in the Canadian Shield. G.G.U. Misc. Pap. 56 and Cdn. J. Earth Sci. 4, 995-1014.
- BULLARD, E., EVERETT, J.E. and SMITH, A.G., 1965. The Fit of the Continents Around the Atlantic. Phil. Trans. Roy. Soc. London 258A, 41-51.
- _____ and GRIGGS, D.T., 1961. The Nature of the Mohorovicic Discontinuity. Geophys. J. Roy. Astron. Soc. 6, 118-123.
- CAREY, S.W., 1958. The Tectonic Approach to Continental Drift. Continental Drift - A Symposium, 177-355. Editor S.W. Carey, Univ. of Tasmania.
- CARMICHAEL, I.S.E., 1964. The Petrology of Thingmuli, a Tertiary Volcano in Eastern Iceland. J. Petrol. 5, 335-360.
- _____, HAMPEL, J. and JACK, R.N., 1968. Analytical Data on the U.S.G.S. Standard Rocks. Chem. Geol. 3, 59-64.
- CHAYES, F., 1964. A Petrographic Distinction between Cenozoic Volcanics in and around the Open Ocean. J. Geophys. Res. 69, 1573-1588.
- _____, 1965. Classification in a Ternary Diagram by Means of Discriminant Functions. Am. Min. 50, 1618-1633.
- _____ and METAIS, D., 1964. Discriminant Functions and Petrographic Classification. Yb. Carnegie Instn. Wash. 63, 179-182.
- CHRISTIE, R.L., 1964. Geological Reconnaissance of Northeastern Ellesmere Island, District of Franklin. Geol. Surv. Canada Mem. 331.
- _____, 1967. Bache Peninsula, Ellesmere Island, Arctic Archipelago. Geol. Surv. Canada Mem. 347.
- CLARK, S.P. and RINGWOOD, A.E., 1964. Density Distribution and Constitution of the Mantle. Rev. Geophys. 2, 35-88.

- CLARKE, D.B., 1965 (unpub.). A Petrographic and Field Study of the Tertiary
Padloping Lavas of Baffin Island. M.A. Thesis, Univ. of Toronto.
- _____, 1967. Tertiary Basalts from Baffin Island and West Greenland.
Proc. Geol. Soc. London 1637, 50-51.
- _____, 1968. The Basalts of Svartenhuk Peninsula, Progress Report.
G.G.U. Report 15, 15-17.
- COHEN, L.H., ITO, K. and KENNEDY, G.C., 1967. Melting and Phase Relations
in an Anhydrous Basalt to 40 Kilobars. Am. J. Sci. 265, 475-518.
- COOMBS, D.S., 1963. Trends and Affinities of Basaltic Magmas and Pyroxenes
as Illustrated on the Diopside-Olivine-Silica Diagram. Min. Soc. Am.
Sp. Pap. 1, 227-250.
- COX, K.G., 1967. Proliferation of Liquid Lines of Descent in Basaltic Magmas.
Proc. Geol. Soc. London 1637, 49.
- _____, and HORNUNG, G., 1966. Petrology of the Karroo Basalts of Basuto-
land. Am. Min. 51, 1414-1432.
- _____, MACDONALD, R. and HORNUNG, G., 1967. Geochemical and Petrographic
Provinces in the Karroo Basalts of Southern Africa. Am. Min. 52,
1451-1474.
- CROMBIE, W.J., 1961. Preliminary Results of Investigations on Arctic Drift
Station Charlie. Geology of the Arctic, 1, 690-708, Editor G.O. Raasch,
Univ. of Toronto Press.
- DAVIDSON, C.F., 1967. The So-Called "Cognate Xenoliths" of Kimberlite.
Ultramafic and Related Rocks, 342-346, Editor P.J. Wyllie, Wiley, New York.
- DAVIS, B.T.C., 1964. The System Diopside-Forsterite-Pyroxene at 40 Kilobars.
Yb. Carnegie Instn. Wash. 63, 165-171.
- _____, and SCHAIRER, J.F., 1965. Melting Relations in the Join Diopside-
Forsterite-Pyroxene at 40 Kilobars and at One Atmosphere. Yb. Carnegie
Instn. Wash. 64, 123-126.

- DAWES, P.R., 1966. Lower Palaeozoic Geology of the Western Part of the North Greenland Fold Belt. G.G.U. Report 11, 11-15.
- DEER, W.A., HOWIE, R.A. and ZUSSMAN, J., 1962. Rock Forming Minerals, Vols. 1, 2 and 4. Longmans, London.
- DIBNER, V.D., HAKKEL', J.J., LITVIN, V.M., MARTYNOFF, V.D. and SHURGAIEVA, N.D., 1965. Geomorphological Map of the Arctic Ocean. Trans. Inst. Arctic Geol. 143, 341-345.
- DRAKE, C.L., CAMPBELL, N.J., SANDER, G. and NAFE, J.E., 1963. A Mid-Labrador Sea Ridge. Nature 200, 1085-1086.
- DREVER, H.I., 1952. The Origin of Some Ultramafic Rocks: A Preliminary Survey of the Evidence For and Against Gravitational Accumulation of Olivine. Medd. Dansk. Geol. Foren. 12, 227-229.
- _____, 1956. The Geology of Ubekendt Ejland, West Greenland, Part II, The Picritic Sheets and Dykes of the East Coast. Medd. om Grøn. 137, Nr. 4.
- _____, 1958. Geological Results of Four Expeditions to Ubekendt Ejland, West Greenland. Arctic 11, 199-210.
- _____ and GAME, P.M., 1948. The Geology of Ubekendt Ejland, West Greenland, Part I, A Preliminary Review. Medd. om Grøn. 134, Nr. 8.
- _____ and JOHNSTON, R., 1957. Crystal Growth of Forsteritic Olivine in Magmas and Melts. Trans. Roy. Soc. Edin. 63, Part II, 289-315.
- DU TOIT, A., 1937. Our Wandering Continents: An Hypothesis of Continental Drifting. Oliver and Boyd, Edinburgh.
- EDWARDS, A.B., 1938. The Formation of Iddingsite. Am. Min. 23, 277-281.
- ELLITSGAARD-RASMUSSEN, K., 1955. Features of the Geology of the Folding Range of Peary Land, North Greenland, Medd. om Grøn. 127, Nr. 7.

- ENGEL, A.E.J., ENGEL, C.G. and HAVENS, R.G., 1965. Chemical Characteristics of Oceanic Basalts and the Upper Mantle. Bull. Geol. Soc. Am. 76, 719-734.
- ENGEL, C.G., FISCHER, R.L. and ENGEL, A.E.J., 1965. Igneous Rocks of the Indian Ocean Floor. Science 150, 605-610.
- ERNST, T., 1965. Do Peridotitic Inclusions in Basalts Represent Mantle Material? The Upper Mantle Symposium, 180-185, New Delhi, 1964.
- ESCHER, A. and BURRI, M., 1967. Stratigraphy and Structural Development of the Precambrian Rocks in the Area North-East of Disko Bugt, West Greenland. G.G.U. Report 13.
- _____ and PULVERTAFT, T.C.R., 1968. The Precambrian Rocks of the Upernavik-Kraulshavn Area (72° - $74^{\circ}15'$ N.), West Greenland. G.G.U. Report 15, 11-14.
- EWING, J. and EWING, M., 1959. Seismic-Refracton Measurements in the Atlantic Ocean Basins, in the Mediterranean Sea, on the Mid-Atlantic Ridge and in the Norwegian Sea. Bull. Geol. Soc. Am. 70, 291-318.
- FAIRBAIRN, H.W., 1953. Precision and Accuracy of Chemical Analysis of Silicate Rocks. Geochim. Cosmochim. Acta 4, 143-156.
- _____ and SCHAIRER, J.F., 1952. A Test of the Accuracy of Chemical Analysis of Silicate Rocks. Am. Min. 37, 744-757.
- _____, SCHLECHT, W.G., STEVENS, R.E., DENNEN, W.H., AHRENS, L.H. and CHAYES, F., 1951. A Cooperative Investigation of Precision and Accuracy in Chemical, Spectrochemical and Modal Analysis of Silicate Rocks. Bull. U.S.G.S. 980.
- FITCH, F.J., 1965. The Structural Unity of the Reconstructed North Atlantic Continent. Trans. Roy. Soc. London 258A, 191-193.
- FLANAGAN, F.J., 1967. U.S. Geological Survey Silicate Rock Standards. Geochim. Cosmochim. Acta 31, 289-308.

- FORTIER, Y.O., BLACKADAR, R.G., GLENISTER, B.F., GREINER, H.R., MCLAREN, D.J.,
MCMILLAN, N.J., NORRIS, A.W., ROOTS, E.F., SOUTHER, J.G., THORSTEINSSON,
R. and TOZER, E.T., 1963. Geology of the North Central Part of the Arctic
Archipelago, Northwest Territories (Operation Franklin). Geol. Surv.
Canada Mem. 320.
- FREUND, R., 1965. A Model of the Structural Development of Israel and Adja-
cent Areas since Upper Cretaceous Times. Geol. Mag. 102, 189-205.
- FULLER, R.E., 1931. The Aqueous Chilling of Basaltic Lava on the Columbia
River Plateau. Am. J. Sci. 21, 281-300.
- GAST, P.W., 1960. Limitations on the Composition of the Upper Mantle. J.
Geophys. Res. 65, 1287-1297.
- _____, 1965. Terrestrial Ratio of Potassium to Rubidium and the Compos-
ition of the Earth's Mantle. Science 147, 858-860.
- _____, 1968. Trace Element Fractionation and the Origin of Tholeiitic
and Alkaline Magma Types. Geochim. Cosmochim. Acta 32, 1057-1086.
- _____, TILTON, G.R. and HEDGE, C., 1964. Isotopic Composition of Lead
and Strontium from Ascension and Gough Islands. Science 145, 1182-1185.
- GIRDLER, R.W., 1966. The Role of Translational and Rotational Movements in
the Formation of the Red Sea and Gulf of Aden. Geol. Surv. Canada Pap.
66-14, 65-77.
- GODBY, E.A., BAKER, R.C., BOWER, M.E. and HOOD, P.J., 1966. Aeromagnetic
Reconnaissance of the Labrador Sea. J. Geophys. Res. 71, 511-517.
- GOLD, D.P., 1963. Average Chemical Composition of Carbonatites. Econ. Geol.
58, 988-991.
- GRAHAM, J.W., 1949. The Stability and Significance of Magnetism in Sedimentary
Rocks. J. Geophys. Res. 54, 131-167.

- GREEN, D.H. and RINGWOOD, A.E., 1963. Mineral Assemblages in a Model Mantle Composition. *J. Geophys. Res.* 68, 937-945.
- _____ and _____, 1964. Fractionation of Basalt Magmas at High Pressures. *Nature* 201, 1276-1279.
- _____ and _____, 1967. The Genesis of Basaltic Magmas. *Contrib. Min. and Pet.* 15, 103-190.
- GREGORY, A.F., BOWER, M.E. and MORLEY, L.W., 1960. Geological Interpretation of Aeromagnetic Profiles from the Canadian Arctic Archipelago. *Geol. Surv. Canada Pap.* 60-6.
- _____, _____ and _____, 1961. Geological Interpretation of Aerial Magnetic and Radiometric Profiles, Arctic Archipelago, Northwest Territories. *Geol. Surv. Canada. Bull.* 73.
- GUNN, B.M., 1966. Modal and Element Variation in Antarctic Tholeiites. *Geochim. Cosmochim. Acta* 30, 881-920.
- HAKKEL', J.J., 1958. Signs of Recent Submarine Volcanic Activity in the Lomonosov Ridge. *Priroda* 4, 87-90.
- HALLER, J., 1961. Account of Caledonian Orogeny in Greenland. *Geology of the Arctic*, Vol. 1, 170-187, Editor G.O. Raasch, Univ. of Toronto Press.
- _____ and KULP, J.L., 1962. Absolute Age Determinations in East Greenland. *Medd. om Grøn.* 171, Nr. 1.
- HAMILTON, W., 1965. Diabase Sheets of the Taylor Glacier Region, Victoria Land, Antarctica. *U.S.G.S. Prof. Pap.* 456-B.
- HARLAND, W.B., 1965. Tectonic Evolution of the Arctic-North Atlantic Region. *Phil. Trans. Roy. Soc. London* 258A, 59-75.
- _____, 1966. A Hypothesis of Continental Drift Tested Against the History of Greenland and Spitsbergen. Cambridge Research.

- _____, SMITH, A.G. and WILCOCK, B., 1964. The Phanerozoic Time-Scale. A Symposium, Geological Society of London.
- HARRIS, P.G., REAY, A. and WHITE, I.G., 1967. Chemical Composition of the Upper Mantle. J. Geophys. Res. 72, 6359-6369.
- HEEZEN, B.C. and EWING, M., 1961. The Mid-Oceanic Ridge and Its Extension through the Arctic Basin. Geology of the Arctic, Vol. 1, 622-642, Editor G.O. Raasch, Univ. of Toronto Press.
- HENDERSON, G. and PULVERTAFT, T.C.R., 1967. The Stratigraphy and Structure of the Precambrian Rocks of the Umanak Area, West Greenland. G.G.U. Misc. Paper 52.
- HESS, H.H., 1960. Stillwater Igneous Complex, Montana. Geol. Soc. Am. Memoir 80.
- HEYWOOD, W.W., 1967. Geological Notes Northeastern District of Keewatin and Southern Melville Peninsula, District of Franklin, Northwest Territories (Parts of 46, 47, 56, 57). Geol. Surv. Canada Pap. 66-40.
- HILGENBERG, O.C., 1966. Evidence of the Kennedy Channel Shear by the Fracture Patterns of Greenland and Northeastern Canada. Geotektonische Forschungen 22, 1-74 (in German).
- HOLMES, A., 1928. Radioactivity and Earth Movements. Trans. Geol. Soc. Glasgow 18, 559-606.
- _____, 1933. A Thermal History of the Earth. Jour. Wash. Acad. Sci. 23, 169-195.
- HOLTEDAHL, H., 1958. Some Remarks on Geomorphology of Continental Shelves off Norway, Labrador, and Southeast Alaska. J. Geol. 66, 461-471.
- HOLTEDAHL, O., 1950. Supposed Marginal Fault Lines in the Shelf Area off Some High Northern Lands. Bull. Geol. Soc. Am. 61, 493-500.
- HOOD, P.J. and BOWER, M.E., 1966. Aeromagnetic Profiles Across Ungava Bay. Geol. Surv. Canada Pap. 66-2, 14-20.

- _____ and GODBY, E.A., 1964. Magnetic Anomalies over the Mid-Labrador Sea Ridge. *Nature* 202, 1099.
- _____, SAWATZKY, P. and BOWER, M.E., 1967. Progress Report on Low-Level Aeromagnetic Profiles over the Labrador Sea, Baffin Bay, and Across the North Atlantic Ocean. *Geol. Surv. Canada Pap.* 66-58.
- HOPE, K., 1967. *Elementary Statistics - A Workbook*. Pergamon Press.
- HUNKINS, K., 1961. Seismic Studies of the Arctic Ocean Floor. *Geology of the Arctic*, Vol. 1, 645-665, Editor G.O. Raasch, Univ. of Toronto Press.
- HYTONEN, K. and SCHAIRER, J.F., 1961. The Plane Enstatite-Anorthite-Diopside and Its Relation to Basalts. *Yb. Carnegie. Instn. Wash.* 60, 125-141.
- IRVING, E., 1958. Rock Magnetism: A New Approach to the Problems of Polar Wandering and Continental Drift. *Continental Drift - A Symposium*, 24-61, Editor S.W. Carey, Univ. of Tasmania.
- ITO, K. and KENNEDY, G.C., 1967. Melting and Phase Relations in a Natural Peridotite to 40 Kilobars. *Am. J. Sci.* 265, 519-538.
- _____ and _____, 1968. Melting and Phase Relations in the Plane Tholeiite-Iherzolite-Nepheline Basanite to 40 Kilobars with Geological Implications. *Contrib. Min. Pet.* 19, 177-211.
- JAMIESON, B.G., 1966. Evidence on the Evolution of Basaltic Magma at Elevated Pressures. *Nature* 212, 243-246.
- JENKINS, R. and DE VRIES, J.L., 1967. *Practical X-Ray Spectrometry*. Philips Technical Library, Eindhoven.
- JOHNSON, G.L. and PEW, J.A., 1968. Extension of the Mid-Labrador Sea Ridge. *Nature* 217, 1033-1034.
- JONES, J.G., 1966. Intraglacial Volcanoes of South-West Iceland and Their Significance in the Interpretation of the Form of the Marine Basaltic Volcanoes. *Nature* 212, 586-588.

- JØRGENSEN, O., 1968. K/Ar Age Determination from Western Greenland II. The Ivigtut Region. G.G.U. Report 15, 87-91.
- KEEN, M.J., BARRETT, D.L., EWING, G.N., LONCAREVIC, B.D. and MANCHESTER, K.S., 1966 (unpub.). The Continental Margin of Eastern Canada: Nova Scotia to Nares Straits.
- KERR, J.W., 1967a. A Submerged Continental Remnant Beneath the Labrador Sea. Earth Planet. Sci. Letters 2, 283-289.
- _____, 1967b. Nares Submarine Rift Valley and the Relative Rotation of North Greenland. Bull. Cdn. Petroleum Geol. 15, 483-520.
- _____, 1968. Southwest Ellesmere Island and Western Devon Island (49B, C; 59A, D) (Operation Grinnell). Geol. Surv. Canada Pap. 68-1A, 199-200.
- KIDD, D.J., 1953. Baffin Island Expedition, 1953: A Preliminary Field Report. Arctic 6, 240-243.
- KING, E.R., ZIETZ, I. and ALLDREDGE, L.R., 1964. Genesis of the Arctic Ocean Basin. Science 144, 1551-1557.
- _____, _____ and _____, 1966. Magnetic Data on the Structure of the Central Arctic Region. Bull. Geol. Soc. Am. 77, 619-646.
- KOCH, B.E., 1963. Fossil Plants from the Lower Palaeocene. Medd. om Grøn. 172, Nr. 5.
- _____, 1964. Review of Fossil Floras and Non-Marine Deposits of West Greenland. Bull. Geol. Soc. Am. 75, 535-548.
- KOCH, L., 1929. Stratigraphy of Greenland. Medd. om Grøn. 73, Nr. 2, 205-320.
- KOPECKY, L. and VOLDAN, J., 1959. Crystallization of Melted Rocks. Geotechnica, svazek 25.
- KRANCK, E.H., 1939. The Rock-Ground of the Coast of Labrador and the Connection between the Pre-Cambrian of Greenland and North-America. Bull. Geol. Comm. Finlande 125, 65-86.

- KRUMBEIN, W.C. and GRAYBILL, F.A., 1965. An Introduction to Statistical Models in Geology. McGraw-Hill.
- KUNO, H., 1965. Fractionation Trends of Basalt Magmas in Lava Flows. J. Petrol. 6, 302-321.
- KUSHIRO, I., 1968. Compositions of Magmas Formed by Partial Zone Melting of the Earth's Upper Mantle. J. Geophys. Res. 73, 619-634.
- _____ and AOKI, K., 1968. Origin of Some Eclogite Inclusions in Kimberlite. Am. Min. 53, 1347-1367.
- _____, SYONO, Y. and AKIMOTO, S., 1967. Effect of Pressure on Garnet-Pyroxene Equilibrium in the System $MgSiO_3 - CaSiO_3 - Al_2O_3$. Earth Planet. Sci. Letters 2, 460-464.
- LARSEN, O., 1966. K/Ar Age Determinations from Western Greenland. G.G.U. Report 11, 57-67.
- _____ and MØLLER, J., 1968. K/Ar Age Determinations from Western Greenland I. Reconnaissance Programme. G.G.U. Report 15, 82-86.
- LAUGHTON, A.S., 1966. The Gulf of Aden, in Relation to the Red Sea and the Afar Depression of Ethiopia. Geol. Surv. of Canada Pap. 66-14, 78-97.
- LE MAITRE, R.W., 1968. Chemical Variation within and between Volcanic Rock Series - A Statistical Approach. J. Petrol. 9, 220-252.
- LE PICHON, X., 1968. Sea-Floor Spreading and Continental Drift. J. Geophys. Res. 73, 3661-3697.
- LEVIN, E.M., ROBBINS, C.R. and MCMURDIE, H.F., 1964. Phase Diagrams for Ceramists, Figs. 853, 855, 869. Am. Ceram. Soc., Columbus, Ohio.
- MACDONALD, G.A. and KATSURA, T., 1964. Chemical Composition of Hawaiian Lavas. J. Petrol. 5, 82-133.
- MACDONALD, G.J.F., 1959. Chondrites and the Chemical Composition of the Earth. Researches in Geochemistry, 476-494, Editor P.H. Abelson, Wiley, New York.

- MATTHEWS, D.H., 1966. The Owen Fracture Zone and the North End of the Carlsberg Ridge. *Phil. Trans. Roy. Soc. London* 259A, 172-186.
- MEIDLER, S.S., 1962. Seismic Activity in the Canadian Arctic 1899-1955. *Seismol. Series of Dominion Observatory Canada*, 1961-3.
- MERCY, E.L.P. and SAUNDERS, M.J., 1966. Precision and Accuracy in the Chemical Determination of Total Fe and Al in Silicate Rocks. *Earth Planet. Sci. Letters* 1, 169-182.
- MUIR, I.D., TILLEY, C.E. and SCOON, J.H., 1964. Basalts from the Northern Part of the Rift Zone of the Mid-Atlantic Ridge. *J. Petrol.* 5, 409-434.
- _____, _____ and _____, 1966. Basalts from the Northern Part of the Mid-Atlantic Ridge II. The Atlantis Collections near 30°N. *J. Petrol.* 7, 193-201.
- MUNCK, S., 1942. The Basalt Breccia (in Rosenkrantz et al., A Geological Reconnaissance of the Southern Part of the Svartenhuk Peninsula, West Greenland). *Medd. om Grøn.* 135, Nr. 3, 43-54.
- _____, 1945. On the Geology and Petrography of the West Greenland Basalt Province. Part V. Two Major Doleritic Intrusions of the Nugssuak Peninsula. *Medd. om Grøn.* 137, Nr. 5.
- MURATA, K.J. and RICHTER, D.H., 1966. The 1959-60 Eruption of Kilauea Volcano, Hawaii: Chemistry of the Lavas. *U.S.G.S. Prof. Pap.* 537-A.
- MURTHEY, V.R. and STUEBER, A.M., 1967. Potassium-Rubidium Ratios in Mantle Derived Rocks. *Ultramafic and Related Rocks*, 376-380, Editor P.J. Wyllie, Wiley, New York.
- NICHOLLS, G.D., NALWALK, A.J. and HAYS, E.E., 1964. The Nature and Composition of Rock Samples Dredged from the Mid-Atlantic Ridge between 22°N and 52°N. *Marine Geol.* 1, 333-343.
- NOCKOLDS, S.R. and ALLEN, R., 1956. The Geochemistry of Some Igneous Rock Series - III. *Geochim. Cosmochim. Acta* 2, 34-77.

- NOE-NYGAARD, A., 1942. On the Geology and Petrography of the West Greenland Basalt Province Pt. III. The Plateaubasalts of Svartenhuk Peninsula. Medd. om Grøn. 137, Nr. 3.
- O'HARA, M.J., 1963a. Melting of Bimineralic Eclogite at 30 Kilobars. Yb. Carnegie Instn. Wash. 62, 76-77.
- _____, 1963b. Melting of Garnet Peridotite at 30 Kilobars. Yb. Carnegie Instn. Wash. 62, 71-76.
- _____, 1965. Primary Magmas and the Origins of Basalts. Scott. J. Geol. 1, 19-40.
- _____, 1967. Mineral Parageneses in Ultrabasic Rocks. Ultramafic and Related Rocks, 393-403, Editor P.J. Wyllie, Wiley, New York.
- _____, 1968. The Bearing of Phase Equilibria Studies in Synthetic and Natural Systems on the Origin and Evolution of Basic and Ultrabasic Rocks. Earth. Sci. Rev. 4, 69-133.
- _____ and MERCY, E.L.P., 1963. Petrology and Petrogenesis of Some Garnetiferous Peridotites. Trans. Roy. Soc. Edin. 65, 251-314.
- _____ and YODER, H.S., 1963. Origin of Igneous Rocks. Yb. Carnegie Instn. Wash. 62, 66-71.
- _____ and _____, 1967. Formation and Fractionation of Basaltic Magma at High Pressures. Scott. J. Geol. 3, 67-117.
- OLIVER, J., EWING, M. and PRESS, F., 1955. Crustal Structure of the Arctic Regions from the Lg Phase. Bull. Geol. Soc. Am. 66, 1063-1074.
- OSBORN, E.F., 1963. Some Experimental Investigations Bearing on the Origin of Igneous Magmas of the Earth's Crust. Estudios Geologicos 19, 1-7.
- OSTENSO, N.A., 1963. Geomagnetism and Gravity of the Arctic Basin. Proc. Arctic Basin Symposium, October 1962, 9-40, Arctic Instn. of North America.

- OXBURGH, E.R., 1964. Petrological Evidence for the Presence of Amphibole in the Upper Mantle and Its Petrogenetic and Geophysical Implications. *Geol. Mag.* 101, 1-19.
- _____ and TURCOTTE, D.L., 1968. Mid-Ocean Ridges and Geotherm Distribution During Mantle Convection. *J. Geophys. Res.* 73, 2643-2661.
- PEACOCK, M.A. and FULLER, R.E., 1928. Chlorophaeite, Sideromelane and Palagonite from the Columbia River Plateau. *Am. Min.* 13, 360-382.
- PECK, L.C., 1964. Systematic Analysis of Silicates. U.S.G.S. Bull. 1170.
- PLOUFF, D., KELLER, G.V., FRISCHKNECHT, F.C. and WAHL, R.R., 1961. Geophysical Studies on IGY Drifting Station Bravo, T-3, 1958 to 1959. *Geology of the Arctic*, Vol. 1, 709-716, Editor G.O. Raasch, Univ. of Toronto Press.
- POWELL, J.L., FAURE, G. and HURLEY, P.M., 1965. Strontium 87 Abundance in a Suite of Hawaiian Volcanic Rocks of Varying Silica Content. *J. Geophys. Res.* 70, 1509-1513.
- POWERS, H.A., 1955. Composition and Origin of Basaltic Magma of the Hawaiian Islands. *Geochim. Cosmochim. Acta* 7, 77-107.
- PULVERTAFT, T.C.R. and CLARKE, D.B., 1966. New Mapping on Svartenhuk Peninsula. G.G.U. Report 11, 15-17.
- PUSHCHAROVSKIY, Y.M., 1960. Some General Tectonic Problems of the Arctic Zone. *Izvest. Akad. Nauk. S.S.R., Ser. Geolog.* 2, 11-24. (Translated A.G.I., 1961).
- RICHARDS, M.B., 1930. The Colorimetric Determination of Manganese in Biological Material. *Analyst* 55, 554-560.
- RILEY, G.C., 1960. Petrology of the Gneisses of Cumberland Sound, Baffin Island, Northwest Territories. *Geol. Surv. Canada Bull.* 61.
- RINGWOOD, A.E., 1962a. A Model for the Upper Mantle, 1. *J. Geophys. Res.* 67, 857-866.

- _____, 1962b. A Model for the Upper Mantle, 2. J. Geophys. Res. 67, 4473-4477.
- _____, 1966a. The Chemical Composition and Origin of the Earth. Advances in Earth Sciences, 287-356, Editor P.M. Hurley, M.I.T. Press, Boston.
- _____, 1966b. The Mineralogy of the Mantle. Advances in Earth Sciences, 357-417, Editor P.M. Hurley, M.I.T. Press, Boston.
- _____, MACGREGOR, I.D. and BOYD, F.R., 1964. Petrological Constitution of the Upper Mantle. Yb. Carnegie Instn. Wash. 63, 147-152.
- RITTMANN, A., 1962. Volcances and their Activity. Interscience Publishers, New York.
- ROSENKRANTZ, A., NOE-NYGAARD, A., GRY, H., MUNCK, S. and LAURSEN, D., 1942. A Geological Reconnaissance of the Southern Part of the Svartenhuk Peninsula, West Greenland. Medd. om Grøn. 135, Nr. 3.
- _____ and PULVERTAFT, T.C.R., 1968. Cretaceous-Tertiary Stratigraphy and Tectonics in Northern West Greenland. (In Press.)
- SHAPIRO, L. and BRANNOCK, W.W., 1956. Rapid Analysis of Silicate Rocks. U.S.G.S. Bull. 1036-C.
- SHAW, D.M., 1968. A Review of K-Rb Fractionation Trends by Covariance Analysis. Geochim. Cosmochim. Acta 32, 573-601.
- STEENSTRUP, K.J.V., 1883. Beretning om Undersølgelsesrejserne i Nord-Grønland i Aarene 1878-80. Medd. om Grøn. 5, Nr. 1.
- STEVENS, R.E., NILES, W.W., CHODOS, A.A., FILEY, R.H., LEININGER, R.K., AHRENS, L.H., FLEISCHER, M. and FLANAGAN, F.J., 1960. Second Report on a Cooperative Investigation of the Composition of Two Silicate Rocks. U.S.G.S. Bull. 1113.
- STUEBER, A.M. and MURTHEY, V.R., 1966. Strontium Isotope and Alkali Element Abundances in Ultramafic Rocks. Geochim. Cosmochim. Acta 30, 1243-1259.

- SUESS, E., 1906. The Face of the Earth, Vol. II, Oxford Press.
- SUKHESWALA, R.N. and POLDERVAART, A., 1958. Deccan Basalts of the Bombay Area, India. Bull. Geol. Soc. Am. 69, 1475-1494.
- SUTHERLAND, P.C., 1853. On the Geological and Glacial Phenomena on the Coast of Davis' Strait and Baffins Bay. Quart. J. Geol. Soc. London 9, 296-312.
- SYKES, L.R., 1965. The Seismicity of the Arctic. Bull. Seismol. Soc. Am. 55, 519-536.
- TAYLOR, F.B., 1910. Bearing of the Tertiary Mountain Belt on the Origin of the Earth's Plan. Bull. Geol. Soc. Am. 21, 179-226.
- _____, 1928a. North America and Asia: A Comparison in Tertiary Diastrophism. Bull. Geol. Soc. Am. 39, 985-1000.
- _____, 1928b. Sliding Continents and Tidal Rotational Forces. The Theory of Continental Drift: A Symposium, 158-177, Editor W.A.J.M. Van Waterschoot van der Gracht, Univ. of Chicago Press.
- TAYLOR, H.P., 1967. Stable Isotope Studies of Ultramafic Rocks and Meteorites. Ultramafic and Related Rocks, 362-372, Editor P.J. Wyllie, Wiley, New York.
- TAYLOR, S.R., 1965. The Application of Trace Element Data to Problems in Petrology. Physics and Chemistry of the Earth, Vol. 6, 133-213.
- THORNTON, C.P. and TUTTLE, O.F., 1960. Chemistry of Igneous Rocks I. Differentiation Index. Am. J. Sci. 258, 664-684.
- THORSTEINSSON, R. and TOZER, E.T., 1960. Structural History of the Canadian Arctic Archipelago since Precambrian Time. Geol. Surv. Canada Pap. 60-7.
- _____ and _____, 1961. Structural History of the Canadian Arctic Archipelago since Precambrian Time. Geology of the Arctic, Vol. 1, 339-360, Editor G.O. Raasch, Univ. of Toronto Press.

TILLEY, C.E., 1961. The Occurrence of Hypersthene in Hawaiian Basalts. Geol.

Mag. 98, 257-260.

_____, YODER, H.S. and SCHAIRER, J.F., 1963. Melting Relations of Basalts. Yb. Carnegie Instn. Wash. 62, 77-84.

_____, _____ and _____, 1964. New Relations on Melting of Basalts. Yb. Carnegie Instn. Wash. 63, 92-97.

_____, _____ and _____, 1965. Melting Relations of Volcanic Tholeiite and Alkali Rock Series. Yb. Carnegie Instn. Wash. 64, 69-82.

_____, _____ and _____, 1967. Melting Relations of Volcanic Rock Series. Yb. Carnegie Instn. Wash. 65, 260-269.

TOBI, A.C., 1961. Plagioclase Determination with the Aid of the Extinction Angles in Sections Normal to (010). A Critical Comparison of Current Albite-Carlsbad Charts. Am. J. Sci. 261, 157-167.

TOZER, E.T. and THORSTEINSSON, R., 1964. Western Queen Elizabeth Islands, Arctic Archipelago. Geol. Surv. Canada Mem. 332.

TROELSEN, J.C., 1950. Contributions to the Geology of Northwest Greenland, Ellesmere Island and Axel Heiberg Island. Medd. om Grøn. 149, Nr. 7.

TRUMPY, R., 1961. Triassic of East Greenland. Geology of the Arctic, Vol. 1, 248-254, Editor G.O. Raasch, Univ. of Toronto Press.

UREY, H.C., 1952. The Planets: Their Origin and Development. Oxford Univ. Press.

VAASJOKI, O., 1965. On Basalt Rocks with Native Iron in Disko, West Greenland. Bull. Comm. Geol. Finlande 218, 85-97.

VAN WATERSCHOOT VAN DER GRACHT, W.A.J.M., 1928. The Theory of Continental Drift: A Symposium, Univ. of Chicago Press.

VINE, F.J., 1966. Spreading of the Ocean Floor: New Evidence. Science 154, 1405-1415.

- WAGER, L.R., 1947. Geological Investigations in East Greenland Part IV. The Stratigraphy and Tectonics of Knud Rasmussens Land and the Kangerdlugssuak Region. Medd. om Grøn. 134, Nr. 5.
- WANLESS, R.K., STEVENS, R.D., LACHANCE, G.R. and RIMSAITE, J.Y.H., 1966. Age Determinations and Geological Studies, K-Ar Isotopic Ages, Report 6. Geol. Surv. Canada Pap. 65-17.
- WEGENER, A., 1924. The Origin of Continents and Oceans. Methuen, London.
- WELCHER, F.J., 1963. Standard Methods of Chemical Analysis, 1191-1194, Van Nostrand, New York.
- WEST, W.D., 1958. The Petrography and Petrogenesis of Forty-Eight Flows of Deccan Trap Penetrated by Borings in Western India. Trans. National Instn. Sci. India 4, No. 1, 1-56.
- WHEELER, E.P., 1960. Anorthosite-Adamellite Complex of Nain, Labrador. Bull. Geol. Soc. Am. 71, 1755-1762.
- WILSON, J.T., 1963. Continental Drift. Scientific American.
- _____, 1966a. A New Class of Faults and their Bearing on Continental Drift. Nature 207, 343-347.
- _____, 1966b. Did the Atlantic Close and then Re-Open? Nature 211, 676-681.
- _____ and CLARKE, D.B., 1965. Geological Expedition to Capes Dyer and Searle, Baffin Island, Canada. Nature 205, 349-350.
- YODER, H.S. and SAHAMA, T.G., 1957. Olivine X-Ray Determinative Curve. Am. Min. 42, 475-491.
- _____ and TILLEY, C.E., 1962. Origin of Basalt Magmas: An Experimental Study of Natural and Synthetic Rock Systems. J. Petrol. 3, 342-532.
- YOE, J.H. and ARMSTRONG, A.R., 1947. Colorimetric Determination of Ti with Disodium-1,2-Dihydroxybenzene-3,5-Disulfonate. Anal. Chem. 19, 100-102.

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